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DEVELOPMENT OF A BROADBAND S-BAND AMPLIFIER

A. D. LaRue

Varian Associates

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13. ABSTRACT

This ~~final~~ report covers development of the VA-915A Twystron hybrid traveling wave tube and construction and test of four models of the tube. Three of these were shipped as final models to RADC in compliance with terms of the contract.

The major subassemblies of the VA-915A are discussed in some detail. In particular, the report covers:

- Electron Gun
- Multicavity Broadband Klystron Assembly
- Centipede TWT RF Output Assembly
- RF Output Window
- Collector
- Electromagnet

The principal conclusion reached in this report is that despite excellent performance, tube potential is seriously restricted by the presence of "Centipede" traveling wave tube rf output circuit oscillatory tendencies. The competing passband modes are in the TM_{01} C-Band loop (coupling element) passband, the TM_{02} X-Band passband, and the π-point region of the TM_{01} S-Band cavity (amplifying) passband. The first two are inhibited in the VA-915A Twystron by magnetic compression of the electron beam. This expedient, however, has a deleterious effect on the amplifier.

Details of illustrations in this document may be better studied on microfiche

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Microwave Device						
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A.D. LaRue

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FOREWORD

This document has been submitted by Varian Associates, 611 Hansen Way, Palo Alto, California, under contract AF 30(602)-4351, Job Order Number 45060000, with Rome Air Development Center, Griffiss Air Force Base, New York. Mr. Dirk T. Bussey (OCTE) was the RADC Project Engineer.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Office (NTIS).

This technical report has been reviewed and is approved.

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FRED I. DIAMOND
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EVALUATOR'S MEMO ON FINAL REPORT

Project No: 4506

Contract No: AF30 (602)-4351

Effort Title: Development of a Broadband S-Band Amplifier

Contractor: Varian Associates, Palo Alto, California

1. This report covers the development of the VA-915 Twystron which was initiated on 28 June 1966. The tube is used as the final power amplifier in the Signal Processing Test Facility operated by RADC at Floyd, New York.

2. The VA-915 represents an advance in the state-of-the-art since it generates the highest known mean peak power (7.15 megawatts) over its operating bandwidth (15% at 3.3 GHz). The tube is designed for pulse compression radar systems of the highest degree of sophistication and therefore, supplies a valuable capability for consideration in future systems design.

Dirk T. Bussey

DIRK T. BUSSEY
Project Engineer
Electron Devices Section

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I. INTRODUCTION

Work on the VA-915A Twystron hybrid traveling wave tube was accomplished under Contract No. AF 30(602)-4351 during the period 28 June 1966 to 29 September 1971. The contracting officer was Bernard N. Haggquist (EMKA). The program monitor was Dirk Bussey (EMATE). The contract called for development of the tube, delivery of two interim models meeting video and impedance requirements but not necessarily meeting rf requirements, and delivery of three final tubes meeting all contractual requirements. Characteristics of the VA-915A are described in "Statement of Work PR A-6-1114," Rome Air Development Center, Griffiss Air Force Base, Rome, New York, dated 25 May 1966. A MIL-E-1 Specification for the tube is included as Appendix A of this final report. Principal operating characteristics of the VA-915A are:

Instantaneous Frequency Bandwidth	3.1 to 3.6 GHz
Peak Power Output (max)	10.0 mw
Mean Peak Power Output (min)	7.15 mw
Beam Voltage (max)	180 kV
Beam Current (max)	151 A
Beam Pulse Width (max)	45 μsec
Rf Pulse Width (max)	40 μsec
Rf Duty	0.0028
Gain (min)	30 dB

Principal use of the tube is in the RADC Signal Processing Test Facility (SPTF). Phase and amplitude response are quite important in the application. Briefly the aim in tube design has been to attain a rounded amplitude response with maximum peak power output near band center and substantially reduced power output at the band edges, concomitant with a phase response as nearly linear as feasible. Details of the rather complex phase and amplitude response requirements may be found in the MIL-E-1 Specification of Appendix A. Generally speaking, the three final model tubes demonstrated performance substantially meeting the principal specification requirements, though in each case deviating in some relatively inconsequential manner from the exact details. Figure 1 is a photograph of the VA-915A.

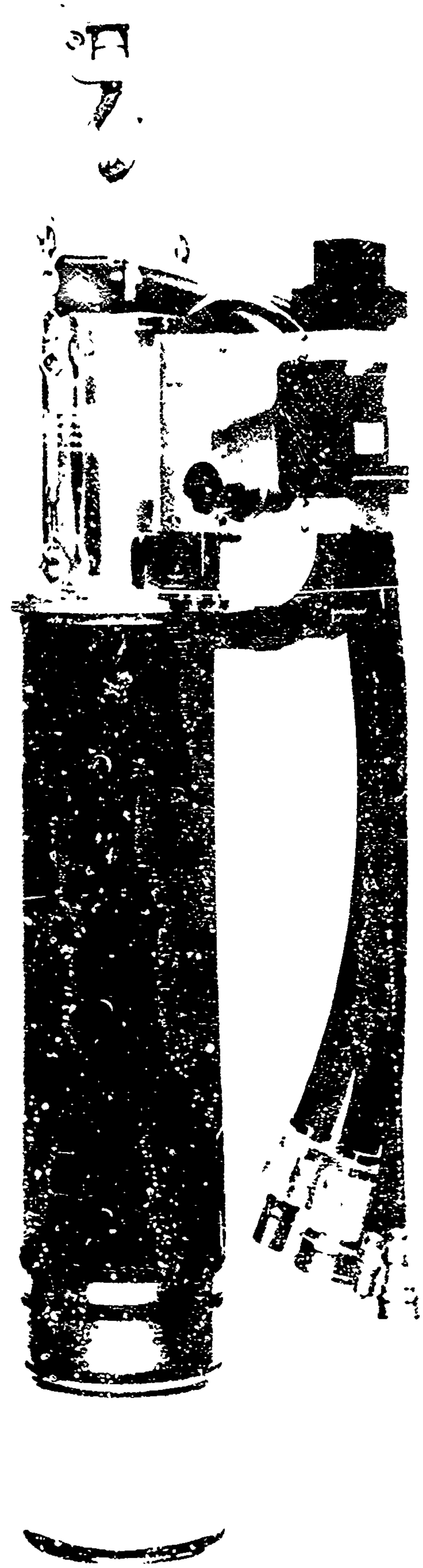


Figure 1. The VA-915A Twystron Traveling Wave Tube
(Tube Length Approximately 57 Inches)

II. ABSTRACT

This final report covers development of the VA-915A Twystron hybrid traveling wave tube and the construction and test of four models of the tube. Three of these were shipped as final models to RADC in compliance with terms of the contract.

The major subassemblies of the VA-915A are discussed in some detail. In particular, the report covers:

Electron Gun
Multicavity Broadband Klystron Assembly
Centipede TWT Rf Output Assembly
Rf Output Window
Collector
Electromagnet

Four tube models are discussed in the report. Three of these were shipped to RADC. A fourth tube is included because of the interesting test data obtained. The model tubes are:

X-3, S/N 101	Shipped
X-8	Accidentally lost, parts salvaged
X-9, S/N 103	Shipped
X-10, S/N 104	Shipped

Models X-3 S/N 101, X-8, and X-9 S/N 103 were tested for amplitude response. Model X-10 S/N 104 was tested for both amplitude and phase response. Detailed test results are given in the report. In general, the models of the VA-915A discussed in the report met or came very close to meeting specification requirements. Other models, discussed in the Monthly and Quarterly Reports, showed serious deviations.

The principal conclusion reached in this report is that despite excellent performance, tube potential is seriously restricted by the presence of "Centipede" traveling wave tube rf output circuit oscillatory tendencies. The competing passband modes are in the TM_{01} C-band loop (coupling element) passband, the TM_{02} X-band passband, and the π-point region of the TM_{01} S-band cavity (amplifying)passband. The first two are

inhibited in the VA-915A Twystron by magnetic compression of the electron beam. This expedient, however, has a deleterious effect on the amplifier.

The Centipede is discussed briefly in a section covering Recommendations. The rough outline of a program for eliminating oscillatory tendencies in the circuit is included. Work on the VA-915A program, taken along with studies of the Centipede at Stanford and elsewhere, indicates the steps to be taken. In principle, the solution is well established. It remains to apply it to this particular tube.

III. DESCRIPTION OF THE VA-915A

1. GENERAL

The VA-915A Twystron hybrid traveling wave tube incorporates an assembly of five broadband klystron stagger-tuned cavities as the rf driver (buncher) section and a "Centipede" TWT rf output section. The two portions of the circuit are designed for gain compatibility near band center, with the requirement that the peak power output fall off toward the band edges. This characteristic makes the device unique in its class. The tube is designed for use in "chirp" (pulse compression) radar systems in which the entire 500 MHz bandwidth is swept with each 40 μs rf pulse, giving a pulse compression ratio of 20,000. The reduction in power output toward the band edges is viewed as a device for simplifying the problem of "weighting" filter design. Such filters are ordinarily employed in pulse compression radar systems to affect the reduction of time side lobes in order to improve range resolution and to reduce ambiguity in a multitarget environment. The rf circuit of the VA-915A is designed for use with an electron beam having a μ Perveance in the range of 1.8 to 2.0. The beam voltage is typically 175 to 180 kV. Figure 2 is a cutaway drawing showing important features of the tube.

Details relating to the work of the program are covered in monthly and quarterly reports. This description of the VA-915A Twystron will touch upon the important characteristics of each of the major portions of the tube design, summarizing details already reported and in some cases expanding upon them.

2. ELECTRON GUN

Figure 3 shows a cross section of the VA-915A electron gun. The device has a μPerveance of 2.0 and an area convergence of 54:1. The emitter is spherical, being fabricated of tungsten impregnated with barium-aluminate. The heater sub-assembly mounts behind the cathode-emitter, operating at an input of close to 555 W,

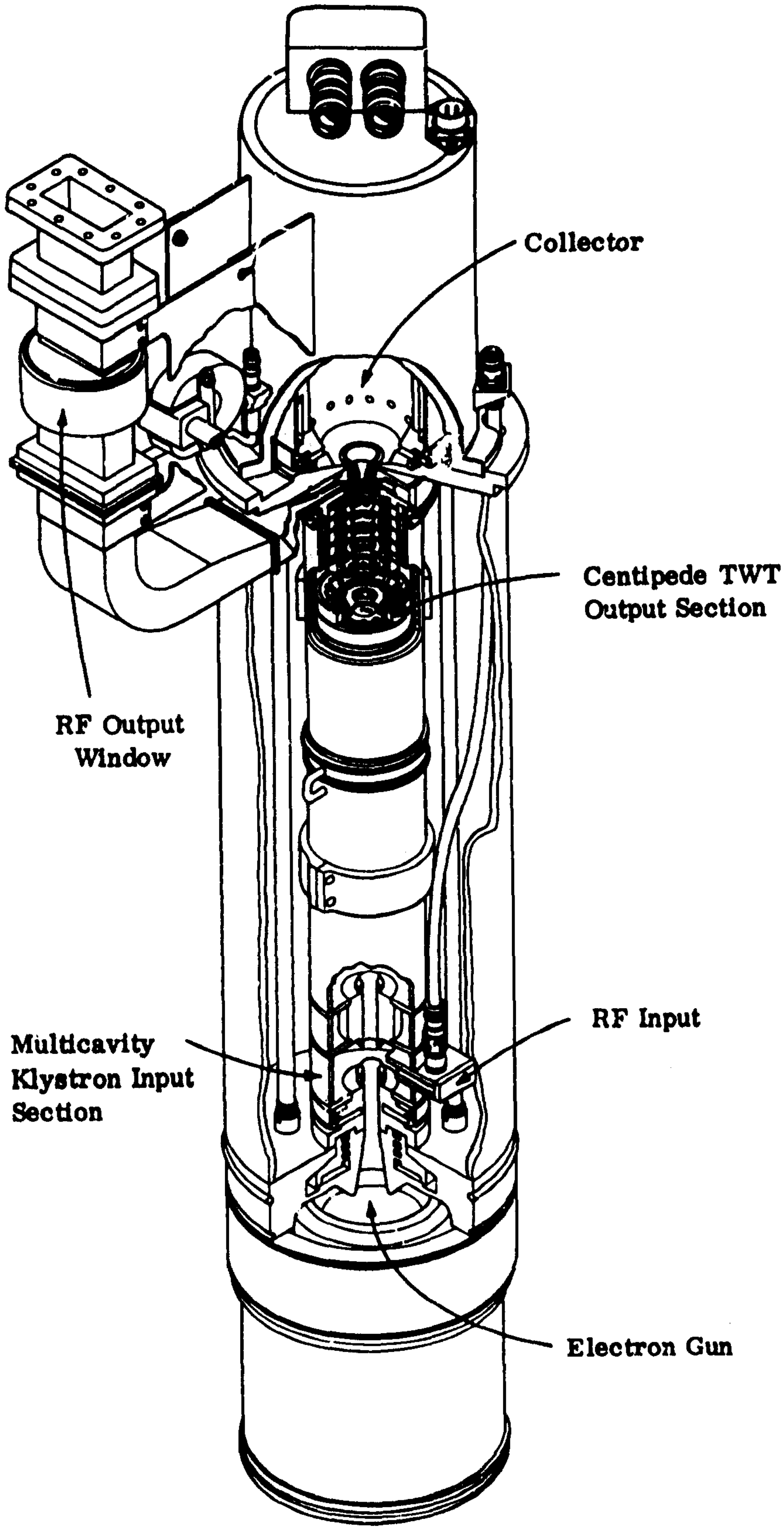


Figure 2. Cutaway Drawing Showing Important Features of the VA-915A Twystron Hybrid Traveling Wave Tube

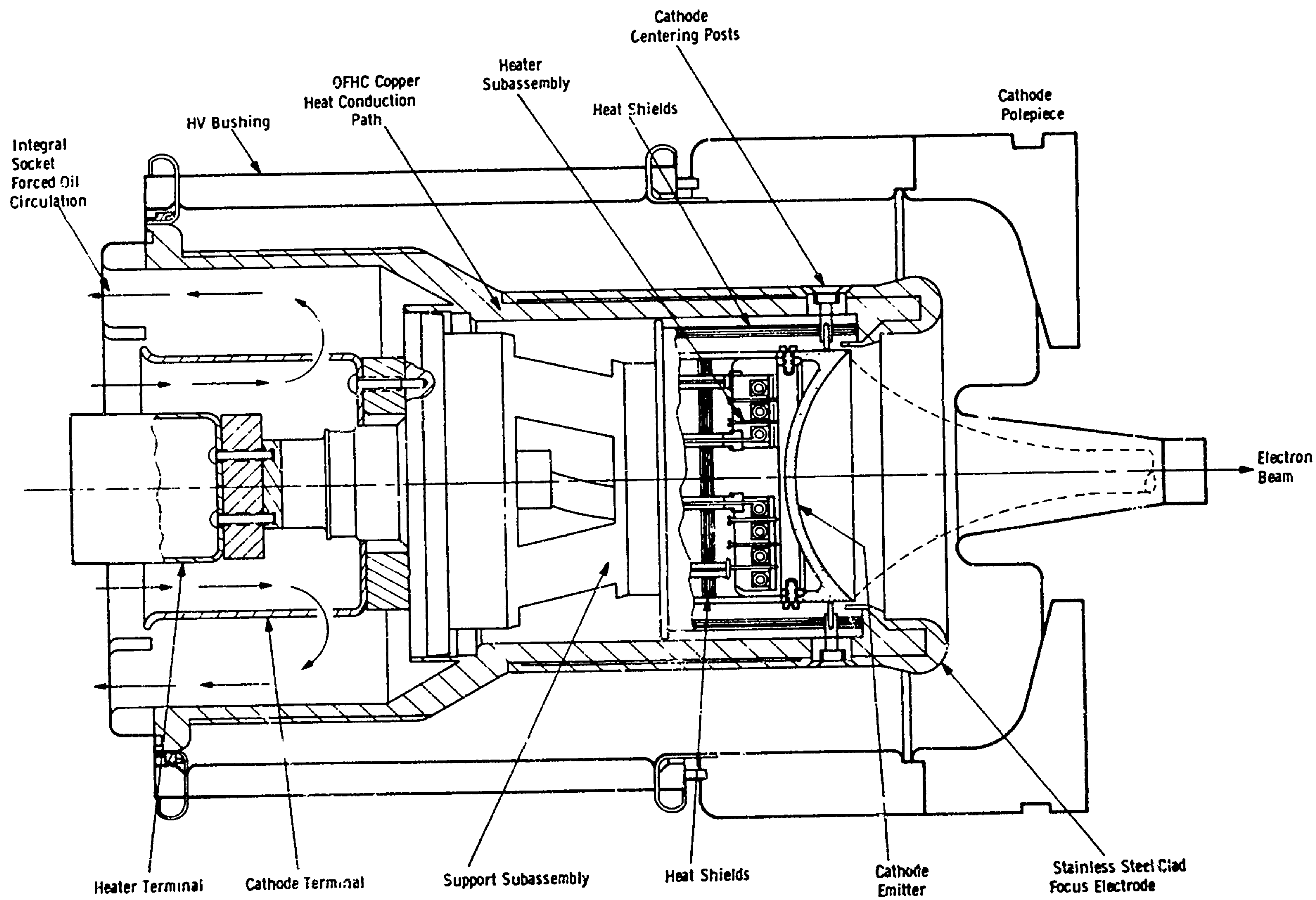


Figure 3. Cross-Section of VA-915A Electron Gun Assembly

typically 15 V at 37 A. Exact heater input requirements vary somewhat from tube to tube. They are listed for the individual tube in the tube data sheet and on the nameplate.

The "hot zone" of the electron gun is carefully heat shielded with multiple layers of thin molybdenum sheet. Thermal paths from the cathode to support structures include appropriate heat choking. Parts located in the "hot zone" are fabricated of tungsten, molybdenum, and alumina. The support subassembly immediately adjacent is of stainless steel. The cathode emitter button is held in place with small molybdenum screws. Other parts in the "hot zone" and the support subassembly are fastened with molybdenum rivets.

The cathode-emitter button is centered with the cylindrical focus electrode by means of alumina centering posts. These are adjusted to provide the small clearances required for thermal expansion. The focus electrode is made of OFHC copper and stainless steel; the former for heat conductivity, the latter for high voltage hold-off characteristics. It is essential that the stainless steel sheathing operate at a low temperature to avoid gassing and the possible evaporation of high vapor pressure constituents. Cooling is provided by means of forced oil circulation over external surfaces of the structure. High voltage insulating oil is pumped into the "bowl" at the end to cool the focus electrode. The tube socket includes a fitting for connecting plastic hose and suitable paths for passage of the coolant. A small one-quarter HP immersed pump-motor may be employed to obtain suitable oil circulation.

The VA-915A electron gun has been studied both by means of computer analyses, providing the basic design, and by means of beam tester experiments. Figure 4 shows the electron beam electrostatic trajectory in the region of the gun. A table of the important characteristics is included with the figure. The beam is one of a class known as "hollowish", from the fact that emission from the cathode-emitter is quite nonuniform. Current density at the edge is somewhat more than double that from the center.

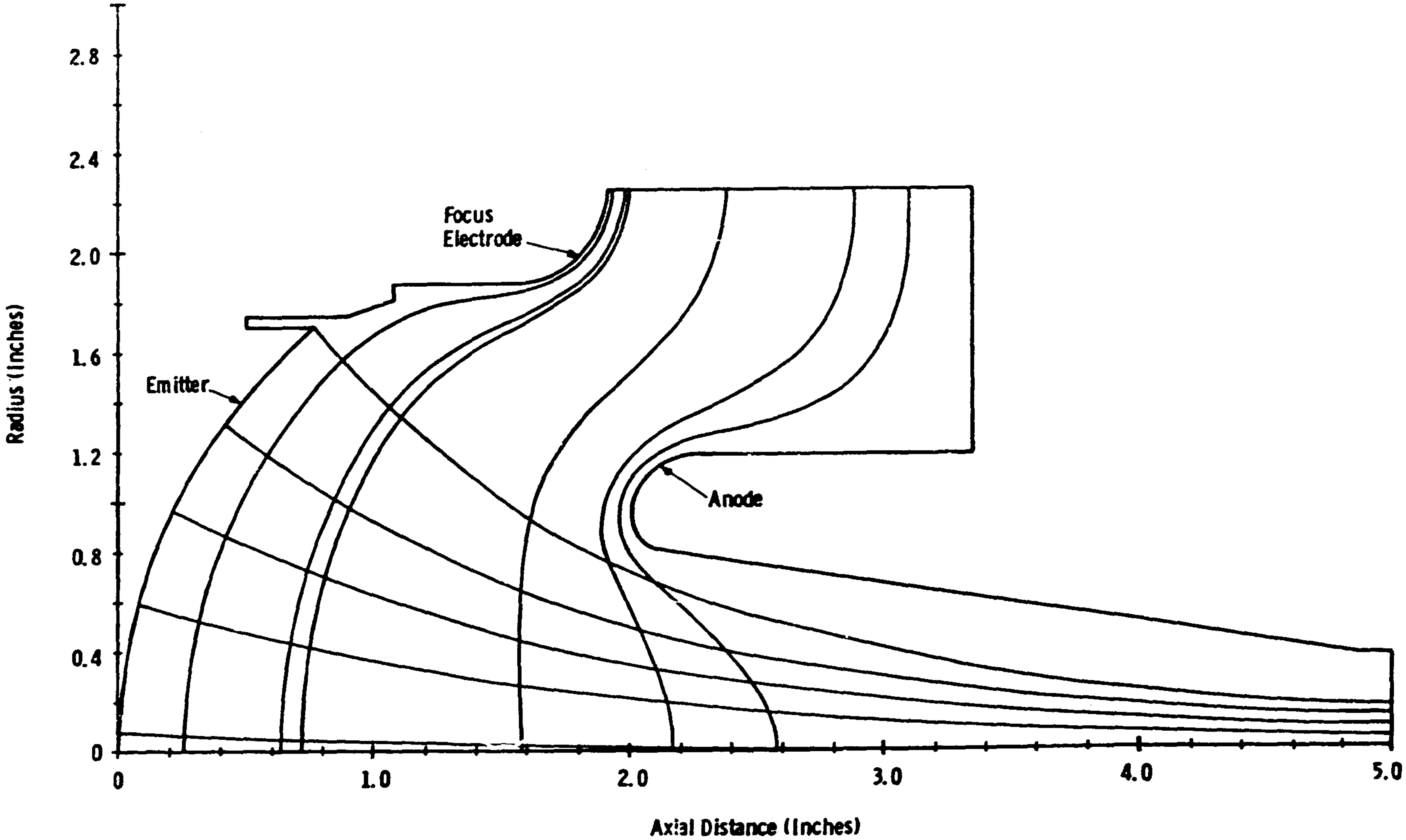


Figure 4. VA-915A Electron Gun Electronic Trajectory Plot (Beam Analyzer and Computer Data)

Figure 5 shows the results of a computer run illustrating this characteristic. Electron beam tests indicated good beam laminarity and retention of the "hollowish" characteristic during beam traverse through the tube. Figure 6 shows the beam profile obtained in beam tester experiments, demonstrating good agreement with earlier computer data for emission from the cathode surface.

The VA-915A electron gun has been operated at voltages up to 200 kV with 45 μsec pulses. Exact limits of the design are not known. Operation of the typical well-seasoned gun at 180 kV and approximately 150 A is characterized by a VacIon level of the order of 10^{-8} Torr and little or no arcing.

3. MULTICAVITY BROADBAND KLYSTRON ASSEMBLY

Figure 7 is a cross-section layout of the VA-915A multicavity broadband klystron rf driver assembly. The characteristics desired in this structure were initially established by computer work augmented by cold test study. Both four cavity and five cavity arrangements were considered. The five cavity assembly worked well in early tubes and has been employed as a standard arrangement ever since Tube X-3. Computer calculations indicated that phase-frequency inflections resulting from the cavities would be acceptable with adequate cavity loading. The characteristics obtained through computer study and cold test experiment for the five-cavity assembly are listed in the following table.

TABLE I

Cavity Number	Req. (MHz)	Q_e	Q_o	Q_b	Q_t	Gap	Drift Length
1	3140	46	100	79	23	0.610	3.500
2	3548	34	100	58	18	0.700	3.000
3	3407	32	100	65	18	0.700	2.250
4	3588		100	57	36	0.700	2.250
5	3605		100	57	36	0.700	1.750

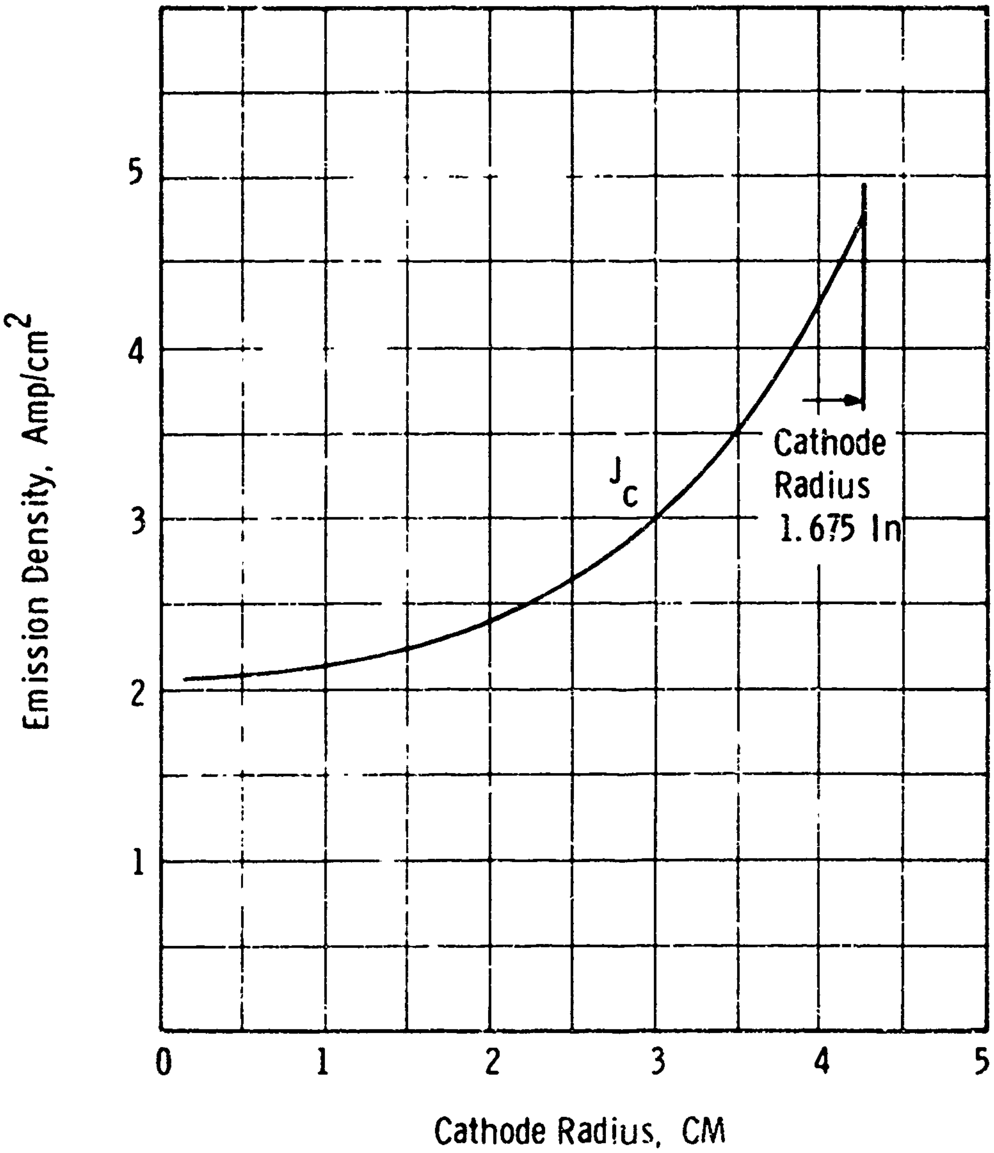


Figure 5. Cathode Emitter Emission Density as a Function of Cathode Radius Data Obtained from Computer Calculations

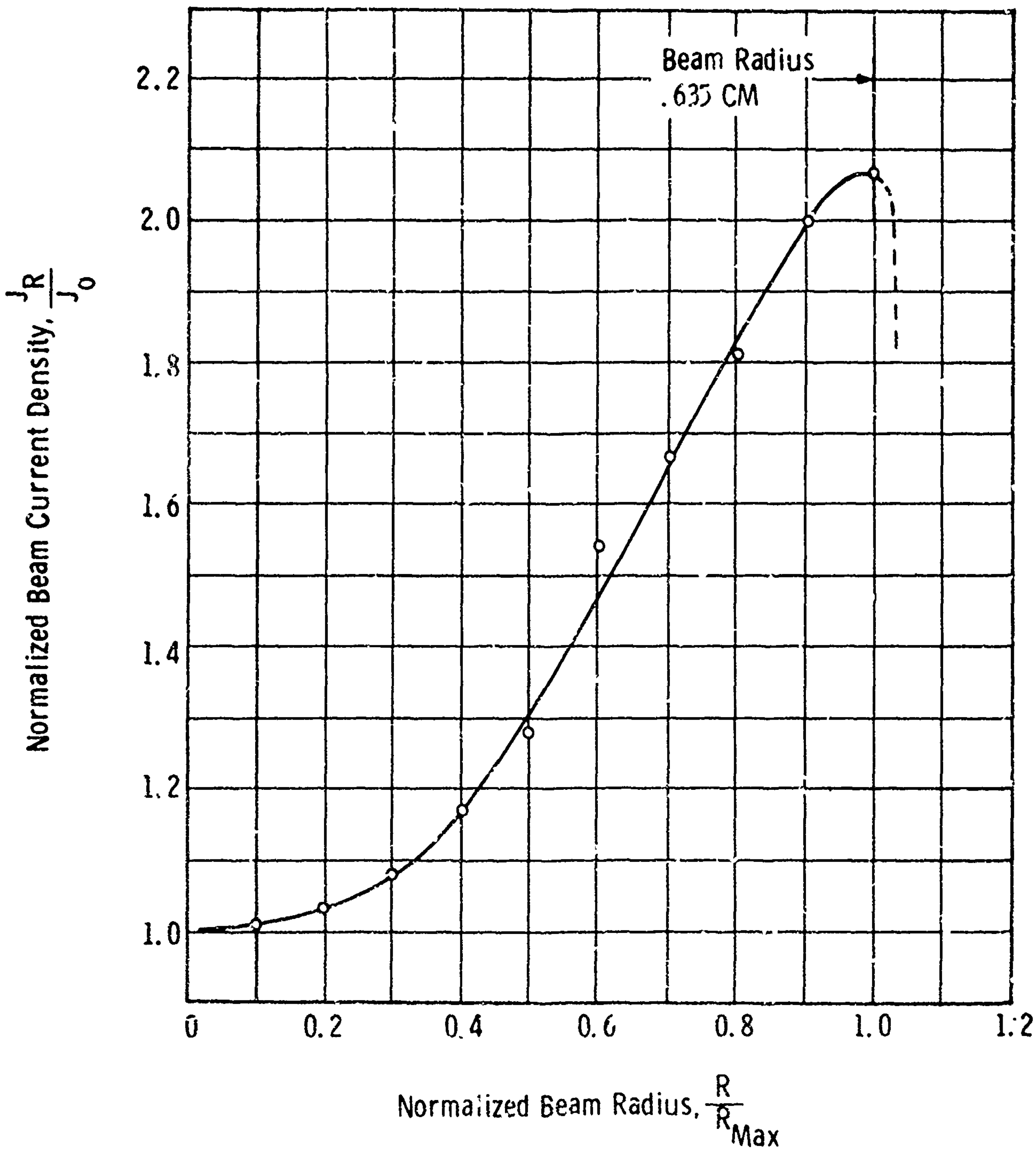


Figure 6. Beam Profile Obtained in Beam Tester Experiments

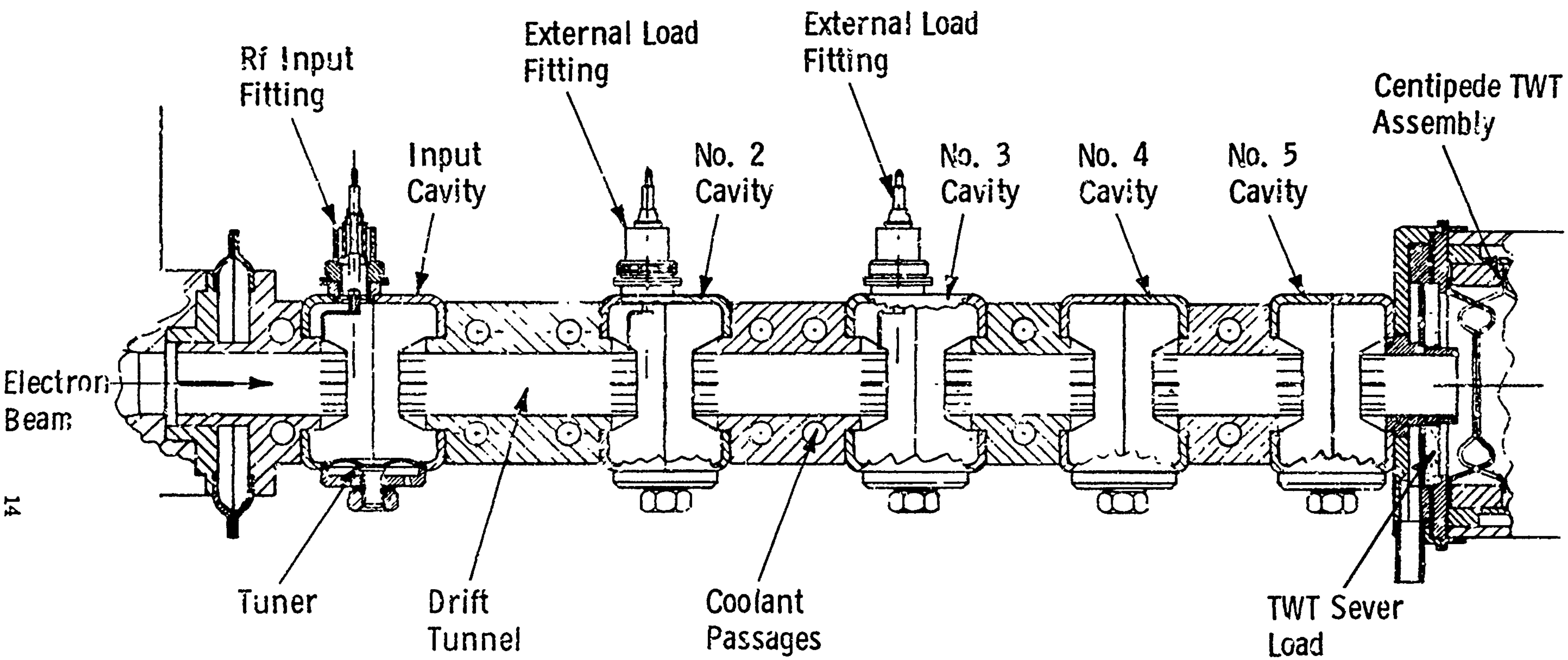


Figure 7. Cross-Section Layout of Multicavity Broadband Kystron Rf Driver Assembly

Cavity No. 1 is the rf input cavity. The first three cavities are externally loaded, as indicated in each case by the listed external Q (Q_e). Loss is applied to the internal walls of each cavity to maintain a low unloaded Q (Q_o). Beam loading also affects the Q (Q_b). These three factors control the total Q (Q_t) of each of the first three cavities. External loading is not applied to the fourth and fifth cavities. In the actual assembly the five cavities are tunable, permitting adjustment of the operating frequencies for tube performance optimization at test.

The coupling arrangements devised to achieve the desired external Qs worked well with cold test cavities that did not include loss on the internal walls, but the addition of this loss adversely affected the coupling. The loading was reduced somewhat. The desired and measured external Qs with lossy cavities were:

TABLE II

COMPUTED AND MEASURED Qs

Cavity Number	Q_{ext} Desired	Q_{oxt} Measured
1	46	59 to 68
2	34	63 to 76
3	32	59 to 61

While some effort was expended in an attempt to increase external load coupling, the problem was never completely resolved. The possibility of employing two external loads per cavity was considered, the added mechanical complexity being a strong deterrent. Tubes constructed with cavities showing the indicated measured external Qs performed well, suggesting that the actual cavity loading employed was not overly critical. In any event, other and more pressing rf circuit problems occupied engineering attention throughout most of the program. These had to do principally with the Centipede TWT rf output, covered in the next section.

4. CENTIPEDE TWT RF OUTPUT ASSEMBLY

4.1 General

Preliminary considerations relating to the VA-915A rf output circuit led to choice of the Centipede TWT assembly. There appeared to be two practicable possibilities at the outset, an alternate choice being the Cloverleaf circuit. Both had been employed in successful high power tubes. It appeared, however, that the Centipede offered certain advantages in terms of bandwidth and mechanical design. With either circuit, as the bandwidth is extended by increased element-to-element coupling, higher frequency modes move downward in frequency, until mode coincidence and competition occur in the main passband. In the Centipede arrangement the higher frequency modes are more widely despersed for a given degree of coupling than are the similar modes of the Cloverleaf structure. Hence, it is possible to realize somewhat greater operating bandwidth with the Centipede. The Centipede circuit has approximately half the cross section of the Cloverleaf at a given design frequency, and the coupling loop structure is simple to fabricate. These two considerations comprise the principal mechanical advantages.

Figure 8 shows a number of full height Centipede circuit elements, as used in the VA-915A Twystron rf output assembly. The two circuit elements in the left foreground are Kanthal-coated. Kanthal is employed as a lossy material on many of the circuit plates, the purpose being to help inhibit oscillation instabilities and to improve the circuit-to-sever termination match. As employed in the VA-915A, the Centipede TWT rf output assembly consists of 11 full height sections, followed by one each of 7/8, 3/4, 5/8, and 1/2 height sections. The latter constitute a velocity taper system introduced to improve operating efficiency and bandwidth. The taper system is nearest to the rf output coupler. At the opposite end of the circuit a sever termination provides a "match" for energy traveling along the circuit in the direction opposed to that of the electron beam.

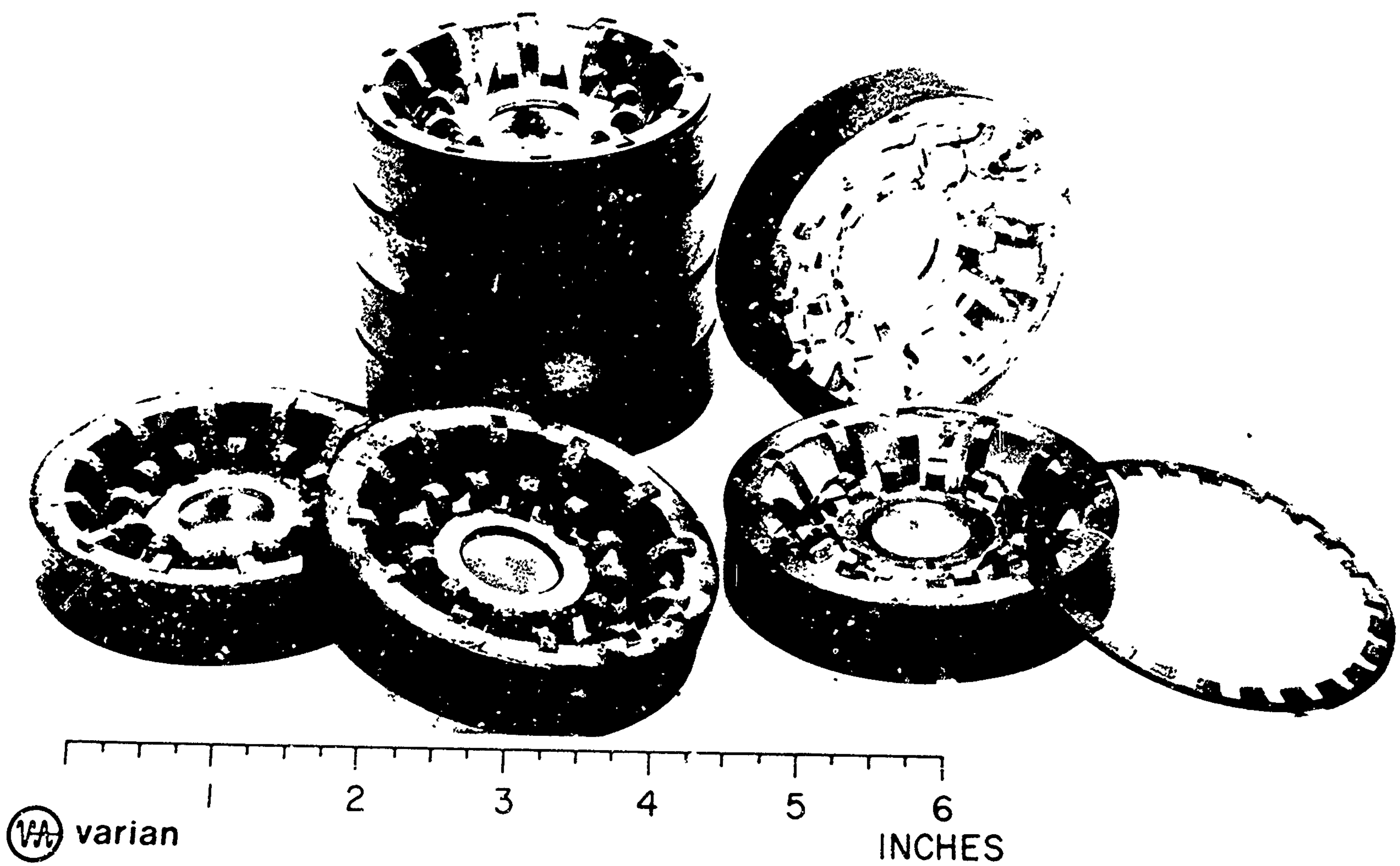


Figure 8. Centipede TWT Rf Output Cricuit Plates and Spacer Ring

4.2 The ω-β Diagram

In considering specific TWT structures it is desirable, almost necessary, to employ the ω-β diagram, where ω is taken as the ordinate and β the abscissa for the periodic transmission system. It is customary to normalize these two factors in various ways, depending on the structure studied. Figure 9 shows an ω-β diagram for the Centipede TWT rf output circuit of the VA-915A Twystron. Here, frequency is taken as the ordinate and phase shift per circuit plate or element section (β L) is taken as the abscissa.

The principal circuit passbands are shown in the frequency region from approximately 3.0 to 9.0 GHz. The TM_{01} S-band cavity passband covers a range of close to 1000 MHz. The 500 MHz segment from 3.1 to 3.6 GHz covers the operating band of the VA-915A. The TM_{02} X-band passband and the TM_{01} C-band loop passband have possible competing oscillatory modes. The TM_{11} antisymmetric passband is included for completeness, though a mode in this passband would have poor coupling to the electron beam unless actual frequency coincidence occurred with the TM_{01} cavity passband. The X-band TE_{11} mode is the calculated cut-off frequency for the drift hole diameter. TE_{11} type mode oscillations have been experienced in tubes similar to the VA-915A.

Two beam voltage operating lines are plotted on the ω-β diagram; one at 60 kV, the other at 175 kV. These lines may be imagined as extending to the origin at zero frequency and phase shift. The operating line for zero voltage would thus extend horizontally from the origin. The rise of a voltage pulse would be represented by the horizontal voltage line (at zero voltage) pivoting at the origin and swinging in an arc up to the position of the beam voltage line representing the voltage at the crest of the beam voltage pulse. At the end of the pulse the sequence of events would be reversed. The points of intersection of the beam voltage operating lines and the various circuit passband modes are regions of possible rf interaction.

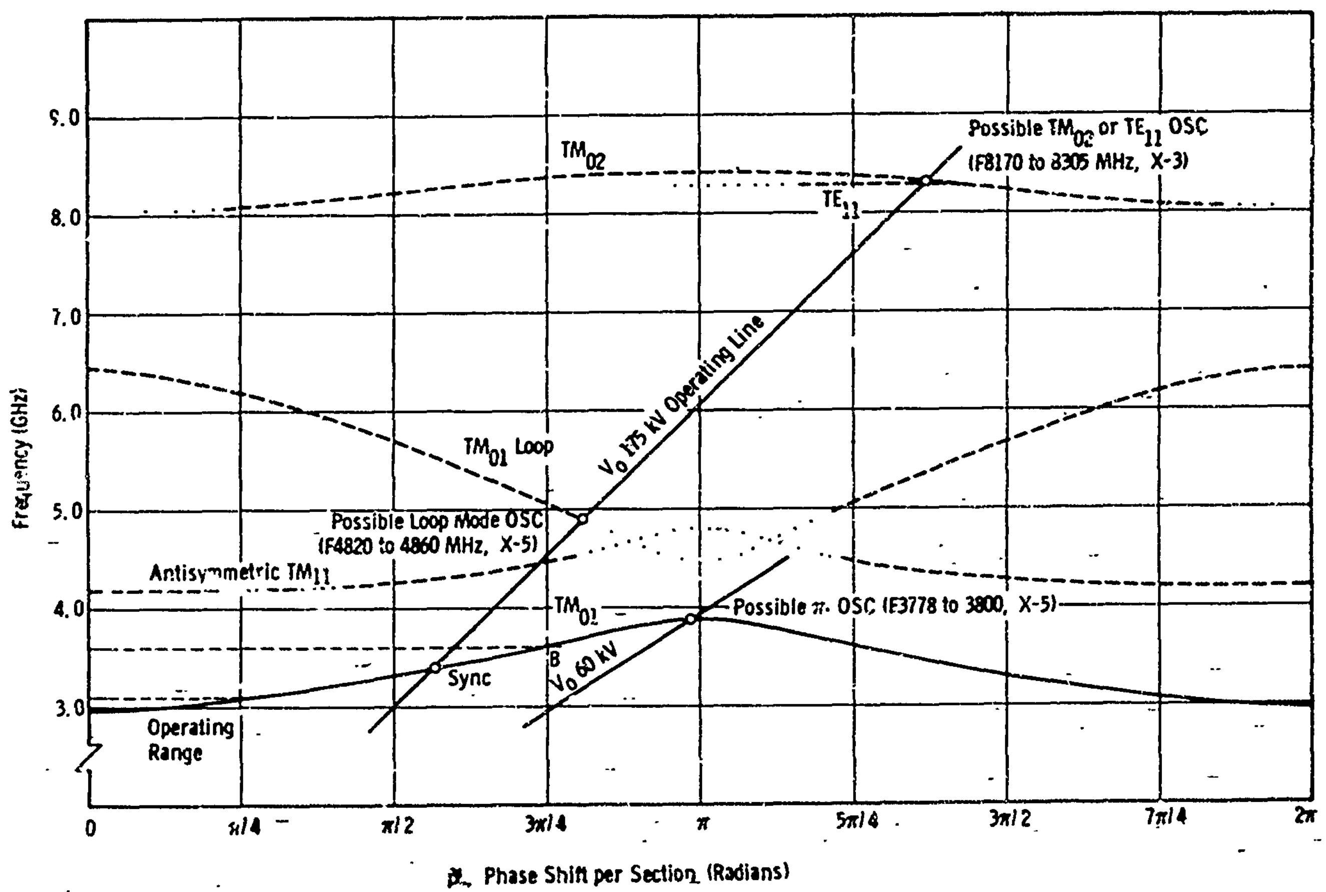


Figure 9. ω-β Diagram for Full-Height Centipede TWT Elements, Showing Relationships Among the Important Circuit Modes and the Beam Voltage

The 60 kV beam voltage operating line, for example, is synchronous at the π-point frequency of the TM_{01} cavity passband. The 175 kV beam voltage operating line is synchronous in the TM_{01} cavity passband near mid-band for the 3.1 to 3.6 GHz operating frequency band. It is also synchronous with the TM_{01} backward wave (reverse slope) C-band loop passband at about 4.85 GHz and with the TM_{02} backward wave X-band passband at about 8.3 GHz. The circuit is well-matched in the region 3.1 to 3.6 GHz, and this portion of the TM_{01} cavity passband is used in normal tube amplification. Large circuit-coupler reflections occur at and near the TM_{01} S-band cavity passband π-point (about 3.8 GHz) however. Typically, there will be oscillations in this region on the rise and fall of the beam voltage as the beam voltage operating line passes through values close to 60 kV. The detected level of this energy should be well down from that of the amplified signal. The beam input at the oscillating point, for example, is about 12 dB down from that occurring at 180 kV. Further, most of the oscillatory signal is trapped within the Centipede structure because of the large signal reflections at the output (mismatch) at or near the π-point frequency. The time of duration or pulse length of the oscillations will depend on the rates of rise and fall of the beam voltage pulse. It takes a finite time for the π-point oscillations to start, and with a sufficiently rapid pulse voltage rise and fall, they may not be detected.

Figure 10 shows ω-β curves for full height, 3/4 height, and 1/2 height Centipede circuit elements in the frequency range 2.8 to 4.0 GHz. These are plotted in terms of the phase shift per full height section. A phase shift of π-radians in a full height section is equivalent to a phase shift of 2π-radians in a 1/2 height section. Thus, the π-point frequency shown for the 1/2 height section coincides with the π-point frequency for a full height section. The two frequencies would agree exactly if the two circuit elements covered the same TM_{01} cavity passband frequency range. An attempt is made to achieve this condition, but the space available for the loops is restricted more and more as the height is redeced. The loop shape is altered in an effort to obtain the desired coupling and bandwidth, but mechanical constraints interfere.

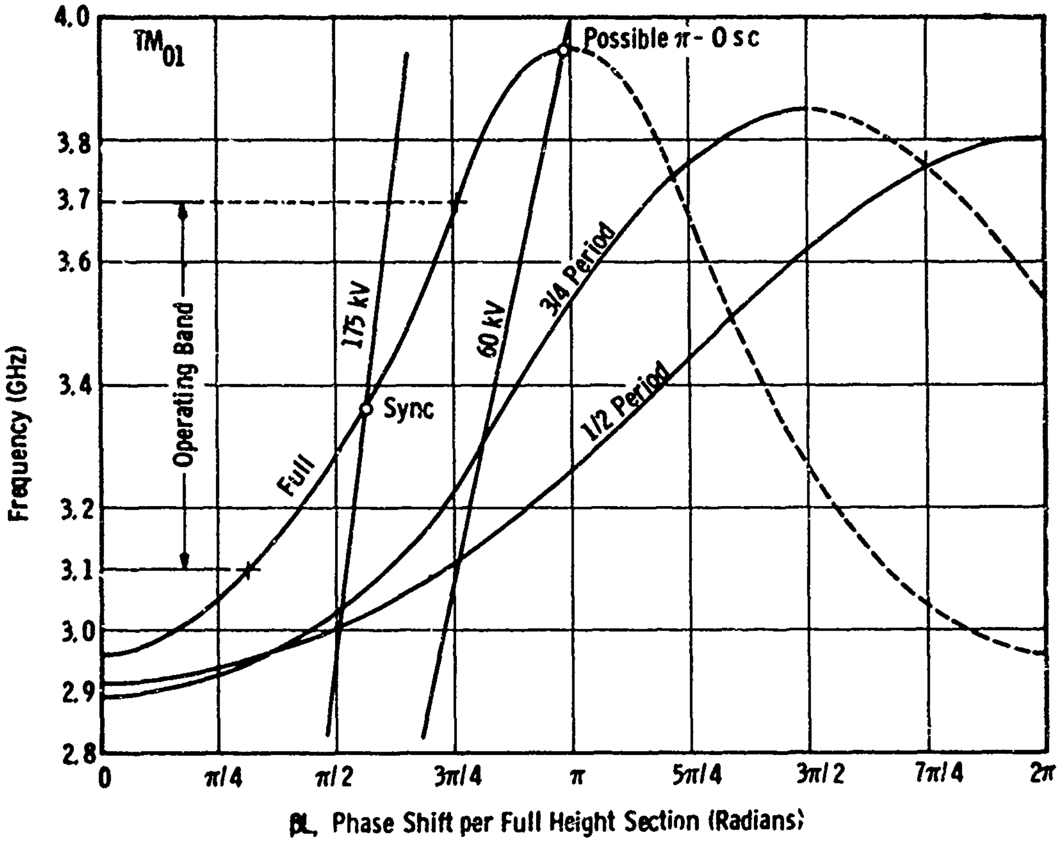


Figure 10. ω-β Diagram of the Main TM_{01} Mode, Showing Full Height, Three-Quarter Height, and One-Half Height Circuit Element Data

These curves were obtained from tests with short stacks of each of the circuit plates. In practice, only one of each type of reduced height sections is used. The actual ω-β characteristic resulting from section combinations is rather complicated. The point to be brought out by the data of Figure 10, however, is that the frequency regions of reduced height circuit synchronism with the beam voltage operating line occur at frequencies lower than that for the full height sections. The reduced height sections, then, contribute to rf output circuit performance in two ways. First, there is enhancement of the tube low frequency response; and second, as the electron beam gives up energy and its velocity is reduced, the reduced height sections tend to remain closer to beam voltage operating line synchronism within the operating frequency band.

Though VA-915A tubes have shown excellent performance as amplifiers in the TM_{01} S-band cavity passband, unfortunately, the prevalence of backward wave oscillations in the TM_{01} C-band loop passband and in the TM_{02} X-band passband have prevented attainment of optimum operating characteristics with the Centipede TWT rf output circuit. Varying degrees of electron beam constraint have been necessary in model tubes in order to suppress oscillations. Adjustment of the magnetic focusing field in the region of rf output circuit to reduce beam size, for example, may be employed to reduce beam coupling to unwanted modes. This may suppress oscillation tendencies, but it also compromises amplifier performance.

Oscillation difficulties of the type described proved to be the most serious electrical problems in development of the VA-915A Twystron. A great deal of effort was expended in circuit studies aiming toward the use of selective loading techniques, in which lossy material is introduced in the circuit in regions where the effect on unwanted modes is much more pronounced than that on the TM_{01} S-band cavity (amplifying) passband. In the Centipede, unfortunately, it has been quite difficult to locate such regions. While some improvement was realized, the primicpal cure for oscillation tendencies has remained in control of the beam size in the rf output circuit, with its attendant performance penalties.

5. RF OUTPUT WINDOW

Two rf output window designs were studied for possible use in the VA-915A. One of these was a conventional waveguide half-wavelength block window fabricated of beryllia, the other was an unusual alumina "pill-box" (or "poker chip") design.

The block window design suffered from the presence of two modes, one just outside the operating bandwidth at either end, though it might have been a useful window structure if assembly problems could have been solved. In the block window configuration, the beryllia material tended to crack at the metal-ceramic interface during brazing operations. The cracks, though often minute, led to rf breakdown. This design was abandoned when acceptable results were obtained with the "pill-box" window.

The "pill-box" window is unusual in that it is exceptionally small for the frequency and power level for which it is designed. An attempt was made to obtain the required 15% mode-free bandwidth by employing dimensions that would place all competing modes on the high frequency side of the VA-915A operating frequency band. As it turned out, the lowest frequency competing mode sometimes occurred at 3602 MHz, compared to a frequency of about 3660 MHz indicated by preliminary calculations. This mode was the TE_{111} "pill-box" cavity mode. At this point, rather than making the window any smaller, it was decided to introduce mode suppression in the form of an $\bar{E}$ field shorting rod placed across the window cavity on the gas side. With the TE_{111} mode suppressed, the next nearest mode should be the TM_{010} mode at about 3900 MHz. This mode was not detected during cold tests.

The VA-915A "pill-box" window dimensions are shown in the follwing table:

TABLE III

ALUMINA "PILL-BOX" WINDOW DESIGN

	Inches
Cavity Diameter	2.400
Cavity Length	0.700
Window Thickness (AL-995)	0.060
Waveguide Size	2.84 x 1.34
Waveguide Radii	0.093
Suppressor Rod Dia.	0.090

Figure 11 shows the principal subassemblies making up the window structure. The periphery of the window is liquid-cooled, but the main cooling comes from the circulation of SF_6 gas across the window face. The alumina window per se is shown in the right foreground mounted centrally in a copper sleeve. The peripheral liquid cooling jacket is in the left foreground. The external flange subassembly with SF_6 gas plenum chambers and fittings is in the left background. The remaining subassembly incorporates a vacuum weld flange, used in joining the assembly to the tube output waveguide.

The rf output window design is capable of an excellent broadband match. Figure 12 illustrates a VSWR versus frequency characteristic observed during cold tests with an AL-300 window. Both AL-300 and AL-995 materials have been employed. The mode-free bandwidth of under 1.1 VSWR indicated by this data is close to 800 MHz centered on 3.35 GHz, a bandwidth of almost 24%. Important also is the fact that a good match is obtained in the range 3.7 to 3.9 GHz, a frequency band covering the π-oscillation frequency of the Centipede TWT rf output circuit. Large reflections from the rf output window structure might enhance any tendency toward π-oscillation. This is an advantage inherent in the "pill-box" over that of the waveguide block window design.

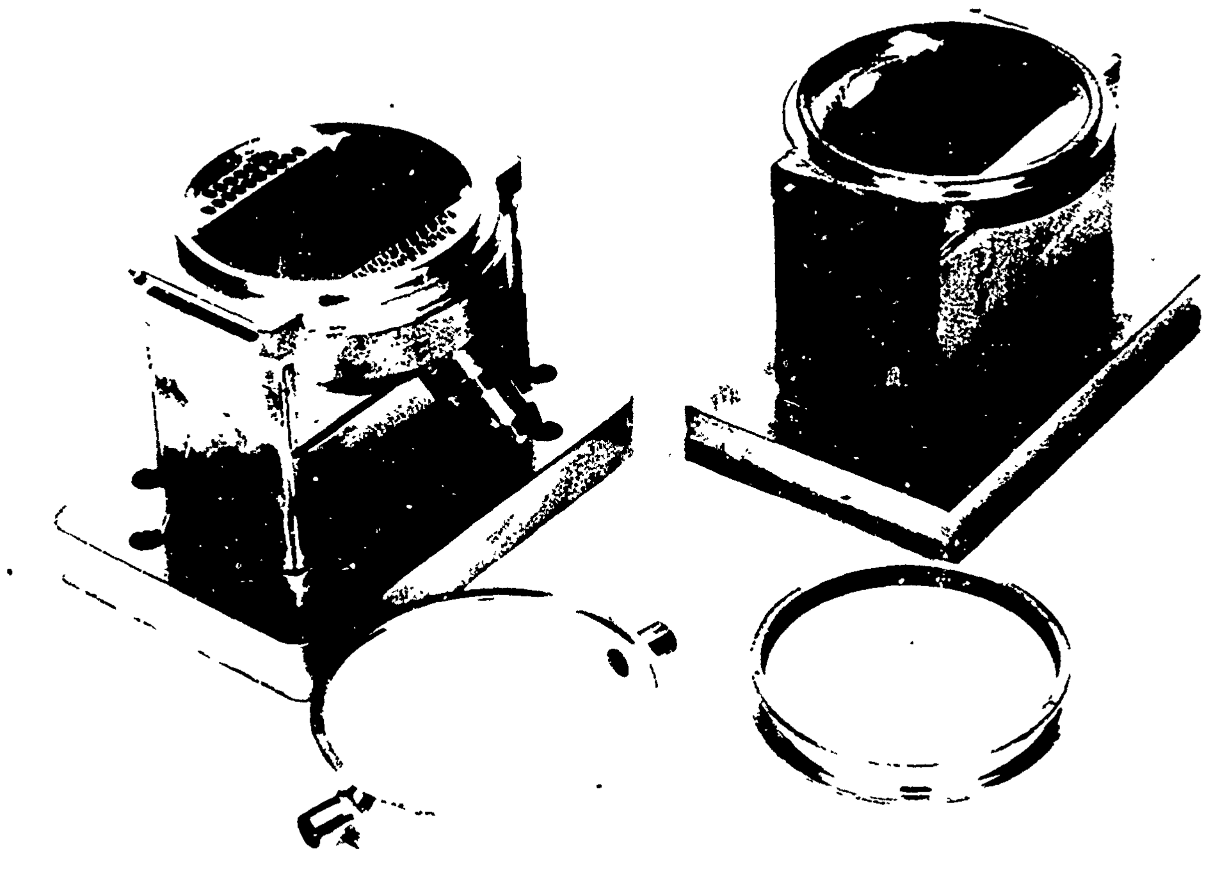


Figure 11. Principal Subassemblies Making up the Rf Output Window Assembly. The window periphery is liquid-cooled. The principal cooling is obtained by circulation of SF_6 gas across the window face.

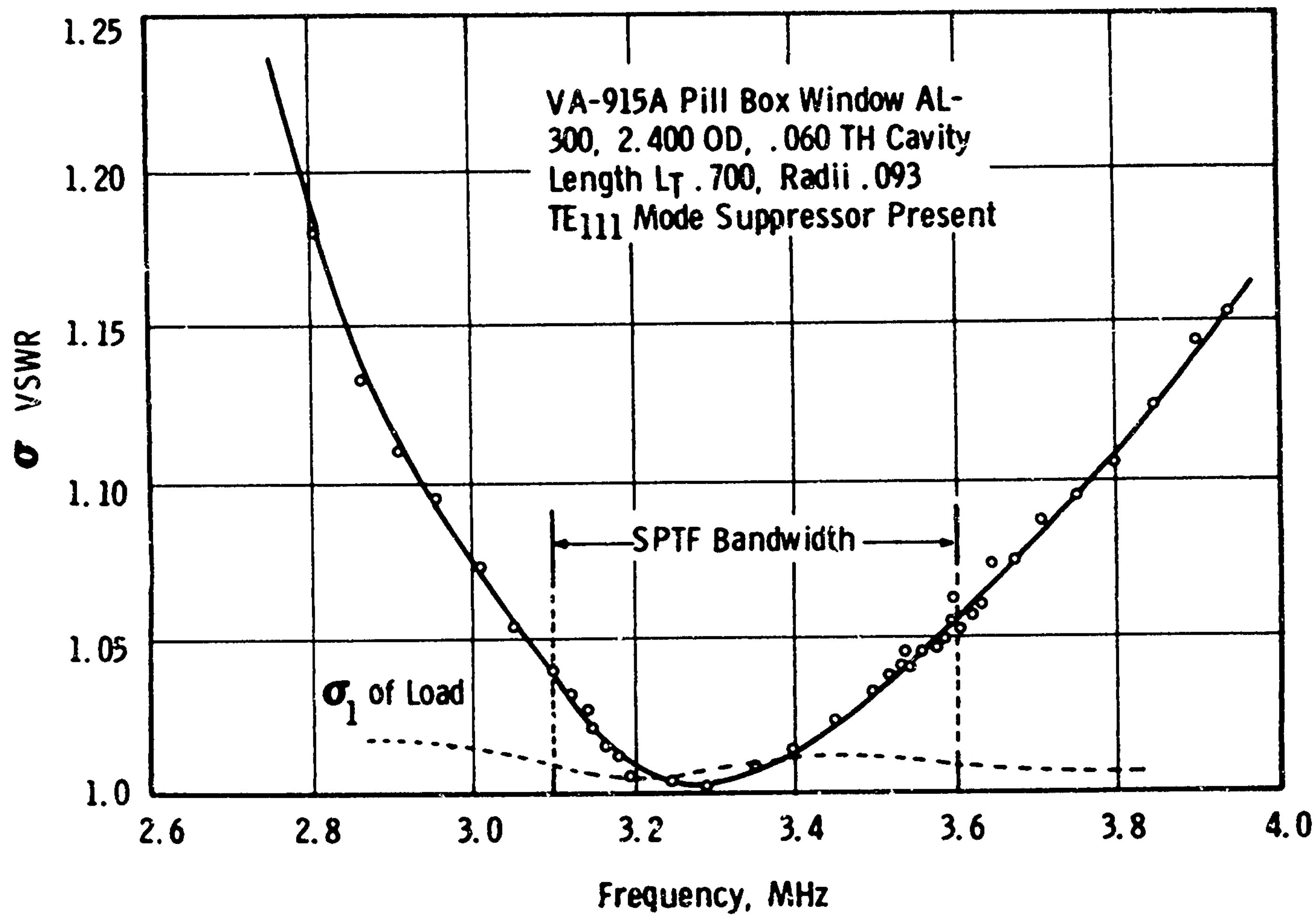


Figure 12. VSWR as a Function of Frequency with Cold Test AL-300 Experimental Pill Box Window

Multipactor effects are reduced in the window design by the application of a titanium film on the vacuum side. The deposition of this material is carefully controlled to achieve multipactor suppression without introducing excessive loss. The SF_6 window face cooling arrangement greatly mitigates the effects of any window heating.

The flexural stress introduced into the window for an applied external SF_6 pressure of 45 psia is close to 18,000 psi. This may be compared to the listed flexural strength of the material (AL-995) of 45,000 psi. These figures indicate a safety factor of about 2.5. The VA-915A window design operates at a higher flexural stress under the stated conditions than does any other "pill-box" design in common use, and it is important that the 45 psia figure not be exceeded.

6. COLLECTOR

Figure 13 is a layout drawing showing important features of the VA-915A collector. The heat exchanger is required to handle the full beam input of close to 77 kW (in the absence of rf drive) with a 60-40% solution of glycol-water as the coolant. The collector is one of conservative design, the surface dissipation problem being treated as though the zone of maximum beam impingement existed throughout the collector. The region of maximum beam dissipation is indicated in Figure 13. The condition shown is for zero rf drive. With rf drive applied, the beam is dispersed over a larger collector area, though the total beam power is less. The acutal power density at the point of maximum heat was determined by means of computer calculations giving representative beam trajectories. Account was taken of the "hollowish" character of the beam, which tends to increase beam power density in the area of maximum dissipation.

It is important to ensure coolant flow conditions that will prevent excessive local temperature rise in this region, regardless of the fact that the overall average

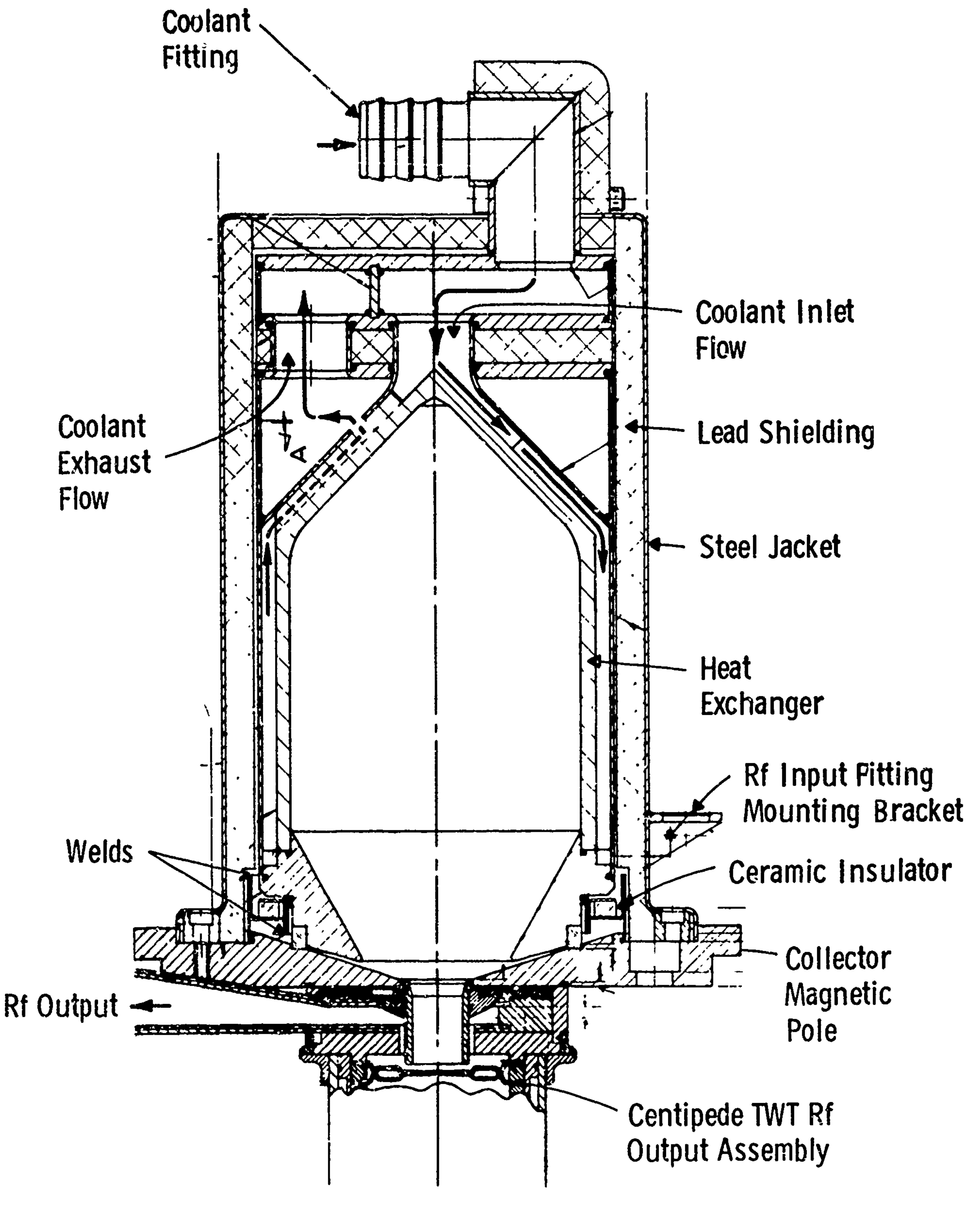


Figure 13. Layout Showing Important Features of the Collector

collector dissipation is relatively modest. Hence, two factors governed the choice of coolant passage geometry and coolant flow. One of these was the arbitrary establishment of a minimum Reynolds number guaranteeing turbulent coolant flow ($R_e = 4000$), the other was a constraint placed on the maximum local coolant temperature ($T \cong 100°C$). Calculations were made for water and for 60-40% glycol-water. Figure 14 is a graph showing the results obtained for water. Figure 15 is a similar graph illustrating the results obtained for 60-40% glycol-water. These data led to required coolant flows in accordance with the following table.

TABLE V

COLLECTOR COOLANT FLOW

Water	T = 12 to 67°C	20 gpm
60-40% Glycol-Water	T = 29 to 48°C	60 gpm

Tests with one model collector indicated that the required 60-40% glycol-water coolant flow would be obtained for a pressure drop across collector, hoses, and fittings of somewhat less than 60 psi.

One unusual feature of the VA-915A collector stems from the operating environment in the SPTF transmitter, near the center of an antenna parabola some 80 feet in the air. The collector coolant is pumped up from ground level. The pressure head and friction throughout the coolant plumbing constitute the major sources of pressure drop. It was important to restrict coolant flow to the minimum necessary. The VA-915A collector has 120 coolant slots, each requiring close to 1 gpm of coolant flow. The ordinary collector passes the coolant through all passages in parallel, using the coolant but once. The peculiar circumstances of VA-915A Tywstron operation led to an arrangement in which the coolant passes from the inlet through alternate passages to the collector bottom, where it is redirected back along the remaining alternate passages to the outlet. Hence, the collector passages use effectively 120 gpm of coolant flow from a supply of 60 gpm. The temperature

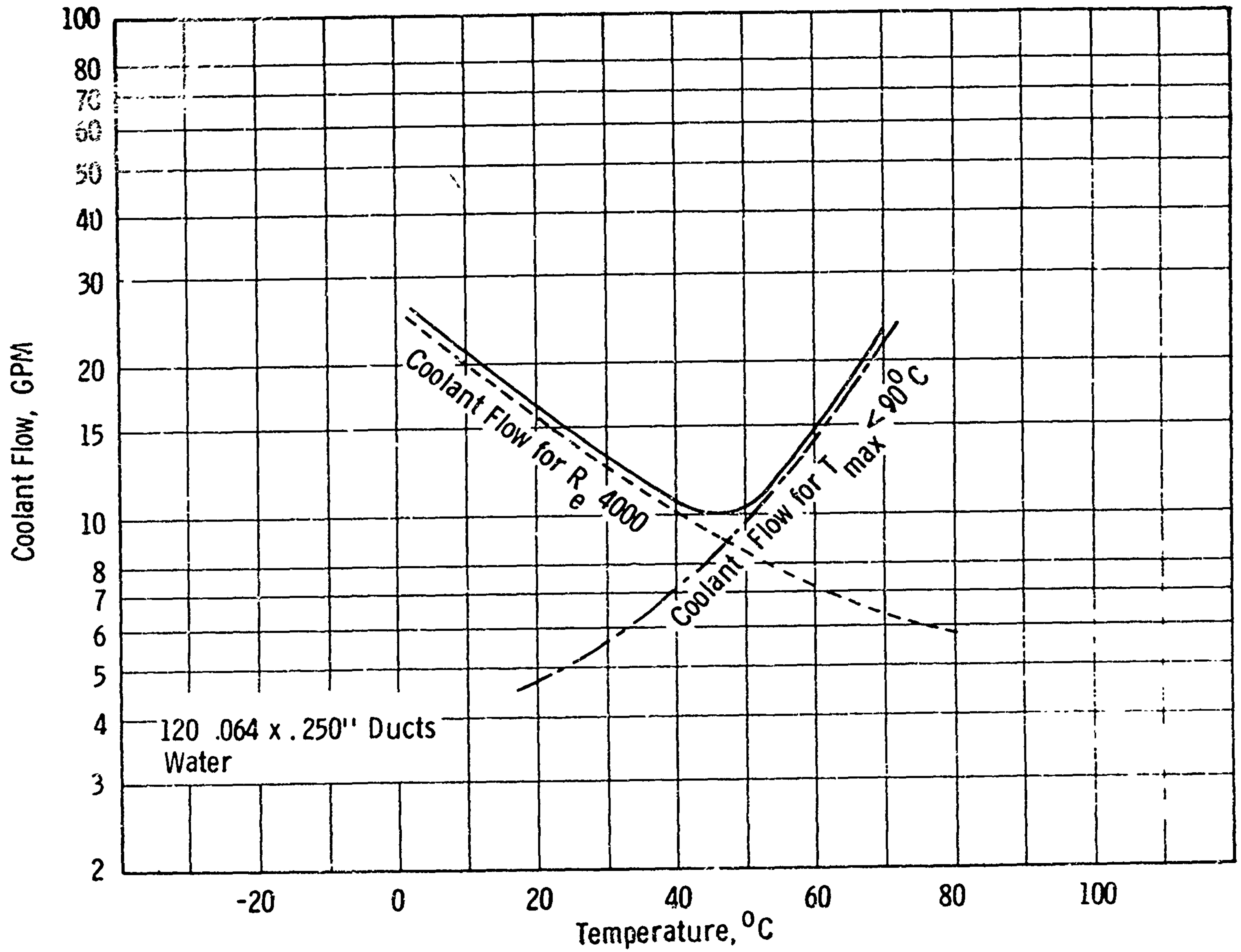


Figure 14. Graph Showing Results of Calculations for Collector Coolant Flow vs Temperature with Water

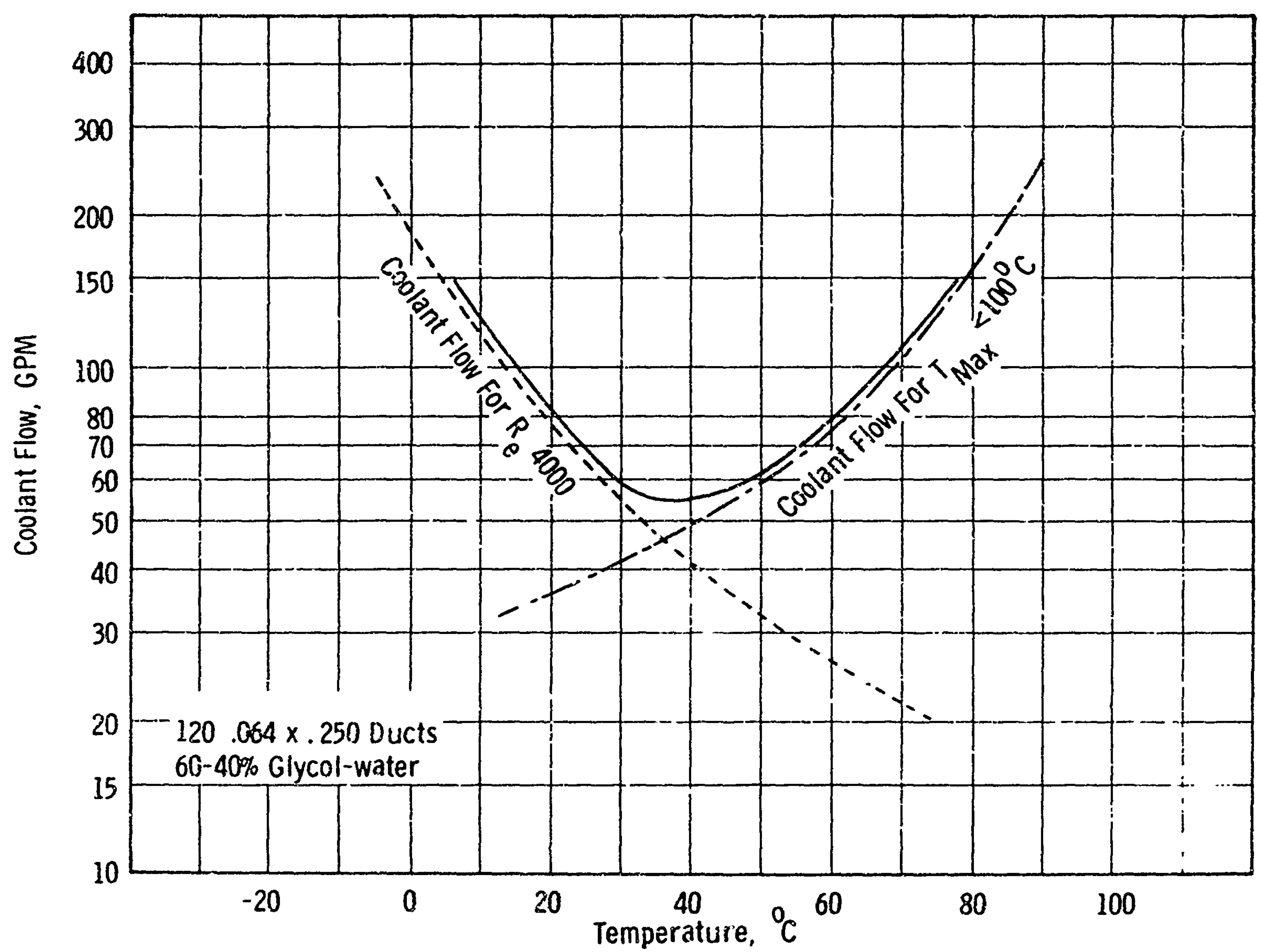


Figure 15. Graph Showing Results of Calculations for Collector Coolant Flow vs Temperature with 60-40% Glycol-Water

rise, of course, is doubled over what it would be in the typical arrangement of passages, though it is small in either case. The double flow system described leads to a large reduction in the friction head loss through the long plumbing system. The design was produced as the result of calculations and tests at Varian and discussion of the problem with cognizant RADC personnel.

7. ELECTROMAGNET

The focusing magnetic field used with the VA-915A Twystron hybrid TWT is supplied by a suitable foil magnet, shown in Drawing No. 027069 Rev. A. The VA-915A uses a confined-flow electron beam, and the magnetic field between polepieces is approximately 2000 Gausses. The magnetic field closely follows the electron beam trajectory in the region of the electron gun.

The electromagnet incorporates four main coils plus a "bucking" coil at the electron gun end of the tube. The "bucking" coil is intended to assist in shaping the magnetic field in the vicinity of the cathode-emitter, though in some cases it is connected in an "aiding" rather than in a "bucking" condition. The nature of the connections to the coils and the current levels to be supplied them are shown in the Tube Performance Data Sheet and on the nameplate of the tube.

IV. TUBE PERFORMANCE

1. GENERAL

The contractual requirements of "Statement of Work PR A-6-1114" called for the delivery of two model tubes meeting all requirements of the Specification and one tube meeting at least 90% of the specification in two of the areas of:

1. Power
2. Phase
3. Bandwidth
4. Spurious Radiation

All other specifications were to be met in entirety. (See Item z of PR A-6-1114.)

The three tubes shipped under terms of the contract were Tube X-3 S/N 101, Tube X-9 S/N 103, and Tube X-10 S/N 104. Tube X-8 showed excellent performance at test and would undoubtedly have been shipped, except for an unfortunate equipment failure that resulted in damage to the rf output window and loss of tube vacuum. Attempts to repair Tube X-8 did not meet with success. Representative test performance data for these four tubes is presented in this section. The results of tests on various other model tubes constructed during the program are given in the monthly and quarterly program reports.

It may be mentioned that despite the excellent tube performance obtained with various models of the VA-915A, in each case the full potential of the tube could not be realized because of the necessity for constraining the beam size in the Centipede TWT rf output circuit to avoid interference from competing oscillatory modes. This problem has been covered briefly in discussion of the Centipede circuit. Possible solutions to the problem are covered in Section V, "Conclusions and Recommendations."

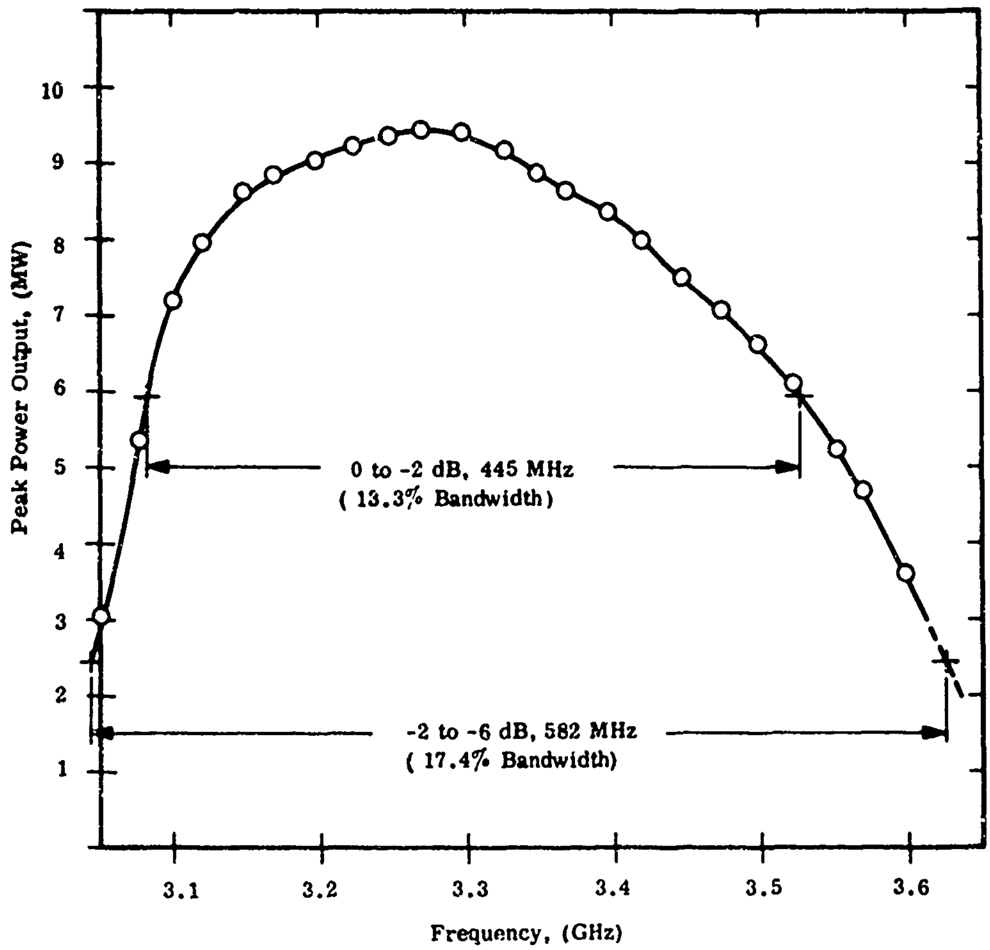
2. TUBE X-3 S/N 101

Figure 16 is a graph illustrating the amplitude response data obtained with Tube X-3. All specifications were met except for the maximum allowable heater input and the band center requirement. The actual frequency of maximum power output was observed at 3270 MHz, as opposed to a specification that this point fall within 3275 to 3425 MHz. The power output at 3275 MHz was very nearly equal to that at 3270 MHz, and Tube X-3 was accepted as a full specification tube. The somewhat excessive heater input was above the specification maximum, though still well within the capabilities of the transmitter heater power supply. Tube X-3 incorporated a new electron gun arrangement designed to obtain good focus electrode cooling. Later modifications in the form of improved heat shielding and choking reduced heater input requirements to a level compatible with the specifications.

Amplitude response tests on Tube X-3 were completed in May 1969, and the tube was ready for phase measurements. The phase measuring equipment was not available for use, however, and it appeared that some delay would occur before phase response tests could be undertaken. The gear was still not ready by July 1969, and the need for a tube at the SPTF site was becoming acute. Phase response measurements were waived, therefore, and the tube was shipped.

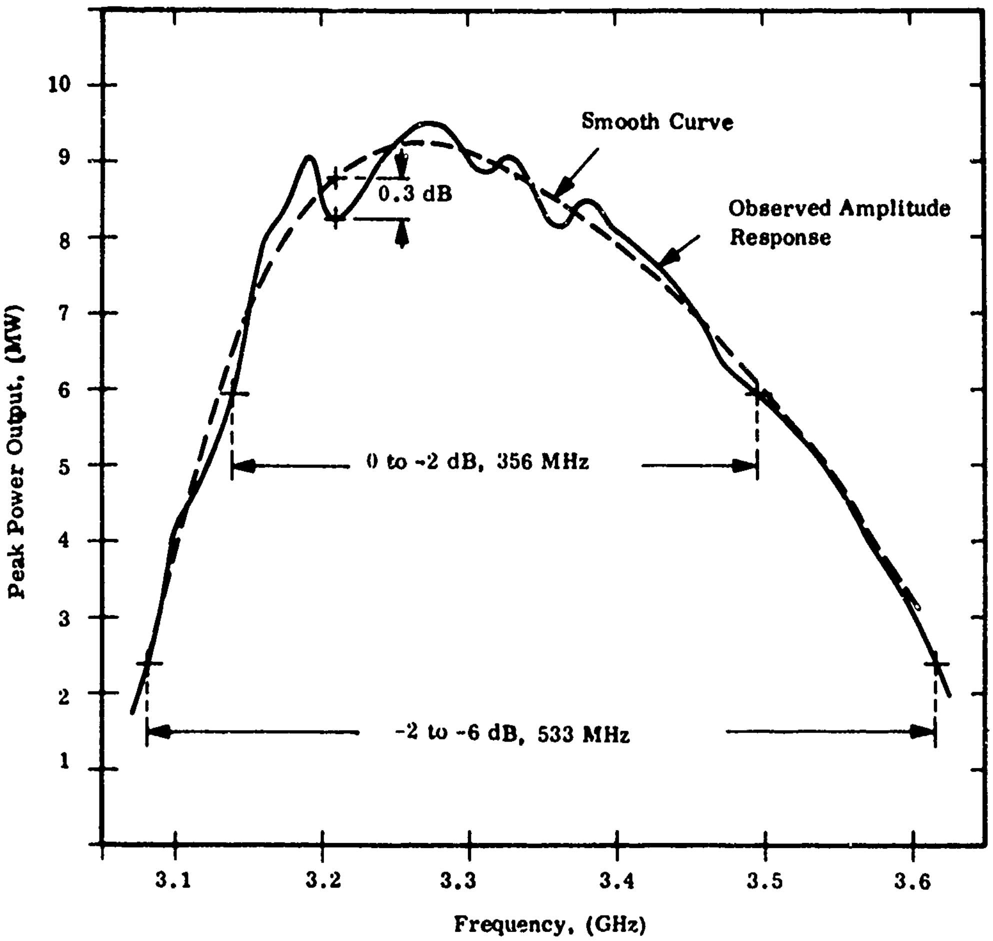
Tube X-3 was employed at the SPTF site during the period July 1969 to July 1970, from reports received at Varian performing quite well. The tube suffered accidental damage at this time, however, and it was returned to Varian for repair. It was repaired, retested, and reshipped in October 1970. The tube is in use at the SPTF site at this writing.

Some insight into the potential of the VA-915A design is indicated by saturated amplitude response data obtained with Tube X-3 and shown in Figure 17. Despite the fact that the electron beam size was constrained during passage through the Centipede TWT rf output assembly to avoid interference from competing oscillatory modes, the



Beam Voltage	175 kV
Beam Current	141 Amp

Figure 16. Saturated Amplitude Response Observed in Tests of VA-915A Tube X-3, S/N 101



Beam Voltage	179 kV	Video Pulse Width	42 μs
Beam Current	149 Amp	Rf Pulse Width	40 μs
Beam μ Perveance	1.85 μ P	Rf Duty	0.0028
Beam Impedance	1280 Ohms	Rf Drive Power	3 kW

Amplitude Response Specifications and Test Results	Test Spec	Test Data
Frequency Range, 3.1 to 3.6 GHz (Min.)		3.1 to 3.6 GHz
Frequency of Max. Power Output (3.35 GHz ± 75 MHz)		3270 MHz
Maximum Peak Power Output	< 10	9.5 MW
Mean Peak Power Output, 3.1 to 3.6 GHz	> 7.15	> 7.15 MW
Gain (Min.)	30	30 dB
Bandwidth, -0 to -2 dB	> 325	355 MHz
Bandwidth, -2 to -6 dB	> 500	533 MHz
Power Variation from Smooth Curve	< 0.5	0.3 dB

Figure 17. Amplitude Response Data for VA-915A Tube X-3, S/N 101

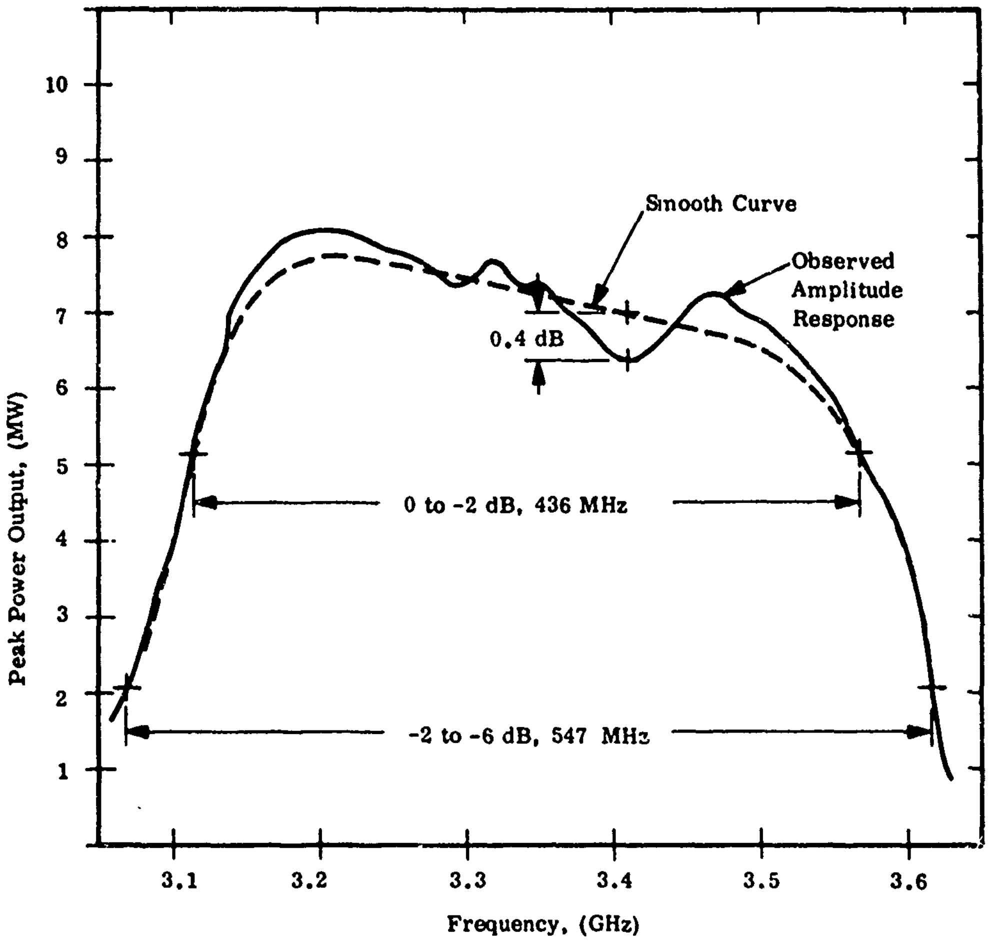
tube showed a maximum peak power output of 9.45 mw at close to 39% efficiency, a -2 dB bandwidth of 445 MHz, and a 6 dB bandwidth of 582 MHz (17.4%).

3. TUBE X-8

Generally successful amplitude response tests were completed with Tube X-8 in March 1970. The data is shown in Figure 18. The frequency of maximum peak power output was somewhat low, though a second power output maxima of slightly lower power occurred near midband. The tube showed excellent performance in all other respects. The maximum peak power output was close to 9.4 mw, the -2 dB bandwidth 425 MHz, and the -6 dB bandwidth was 545 MHz (16.2%). The mean peak power output across the 3.1 to 3.6 GHz band was 7.8 mw, the highest produced by any of the VA-915A Twystron tubes.

Tube X-8 was set aside until May 1970, at which time arrangements were made for phase response testing. During the preparations, after minor adjustments were made in rf drive level and in the phase measuring equipment circuitry, the tube was turned off for the night as usual. The actual phase response tests were to have been performed the next day. The next morning, however, the rf output window was found to be broken and the tube down to SF_6 gas. The indicated pressure in the output waveguide was 60 psig, and it may have been even higher. The only explanation that could be found for the overpressure was the presence of grit in the SF_6 pressure-regulating valve.

Tube X-8 showed exceptional test performance, and the data is included in this report for completeness. The tube would undoubtedly have been shipped except for this unfortunate accident. Attempts to repair the device proved unsuccessful.



Beam Voltage	180 kV	Video Pulse Width	45 μs
Beam Current	149 Amp	Rf Pulse Width	40 μs
Beam μ Perveance	1.95 μ P	Rf Duty	0.0028
Beam Impedance	1208 Ohms	Rf Drive Power	4 kW

Amplitude Response Specifications and Test Results	Test Spec	Test Data
Frequency Range, 3.1 to 3.6 GHz (Min.)		> 3.1 - 3.6 GHz
Frequency of Max. Power Output (3.35 GHz ± 75 MHz)		3200 MHz
Maximum Peak Power Output	≤ 10	8.1 MW
Mean Peak Power Output, 3.1 to 3.6 GHz	> 7.15	6.6 MW
Gain (Min.)	> 30	29 dB
Bandwidth, -0 to -2 dB	> 325	436 MHz
Bnadwidth, -2 to -6 dB	> 500	547 MHz
Power Variation from Smooth Curve	< 0.5	0.4 dB

Figure 18. Amplitude Response Data for VA-915A Tube X-8

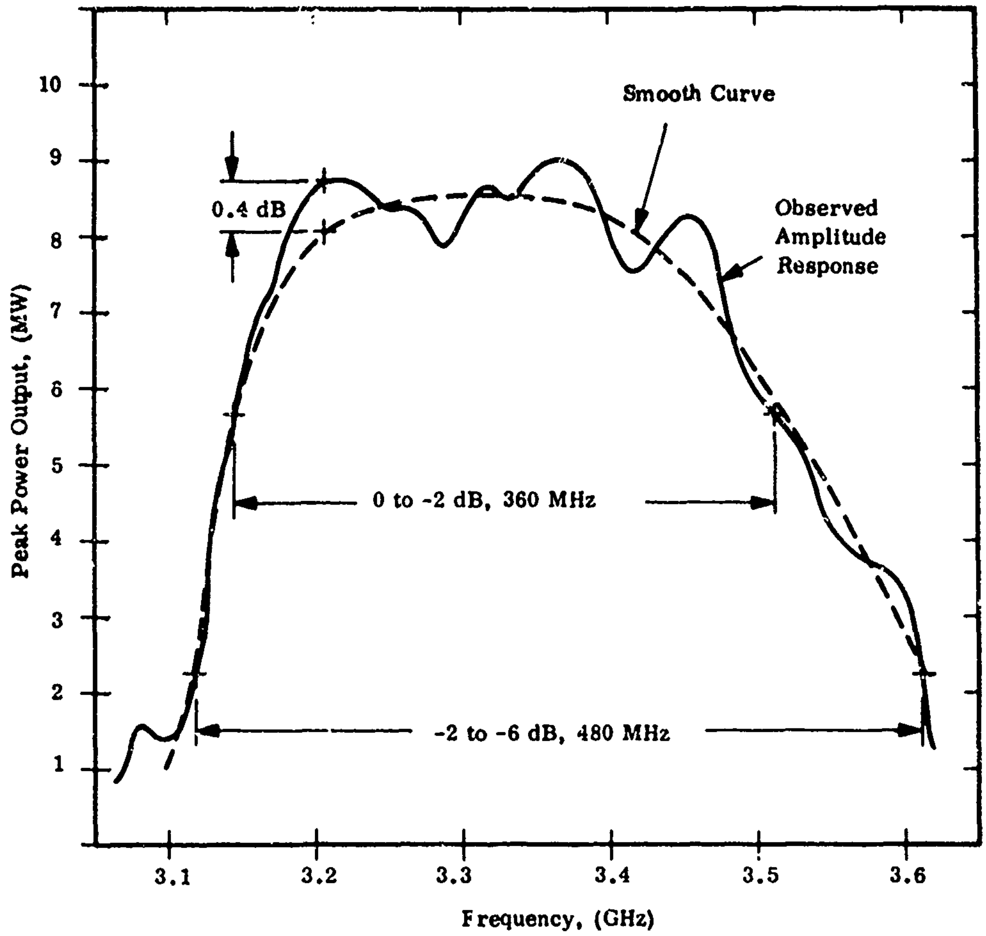
4. TUBE X-9 S/N 103

Tube X-9 was repaired and reprocessed a number of times before reaching final test in March 1971. At this point the tube was identified as X-9R4 in the records. The amplitude response data observed in test is shown in Figure 19. The overall bandwidth was somewhat less than that obtained with earlier tube models, and the mean peak power output across the band was also slightly low. The tube bandwidth covered 94% of the required SPTF 3.1 to 3.6 GHz band, however, and the mean peak power output of 6.95 mw was 97% of the specification requirement In accordance with contractual agreements, the tube was accepted by RADC as a tube meeting at least 90% of the amplitude response requirements in the areas of power output and bandwidth and fully meeting all other amplitude response requirements. Phase response tests were waived by RADC, and the tube was shipped to the SPTF site in March 1971. It is still in service.

5. TUBE X-10 S/N 104

Tube X-10 reached final test in May 1971. Amplitude and phase response tests were completed in August 1971. Amplitude response data is shown in Figure 20, phase response data in Figures 21 and 22.

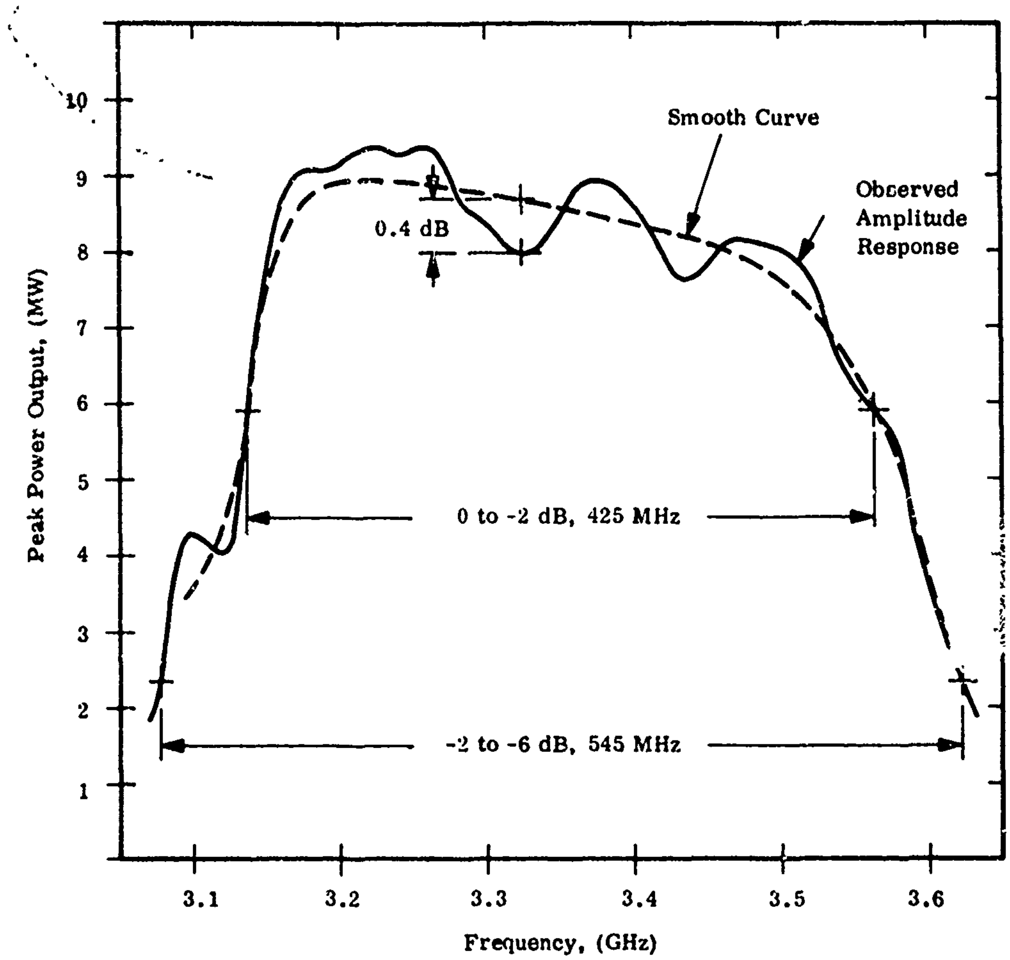
Tube X-10 showed exceptional bandwidth, but the mean peak power output across the required SPTF bandwidth was somewhat low. The -6 dB bandwidth was 547 MHz (109% of specification), while the mean peak power output across the SPTF 3.1 to 3.6 GHz bandwidth was 6.6 mw (92.4% of specification). This discrepancy was waived by RADC. In addition, maximum power output occurred away from band center and at a frequency close to 3.2 GHz, although a second power output p . of only slightly lower power output occurred close to band center. This deviation was also waived. In all other respects, Tube X-10 was an excellent model.



Beam Voltage	175 kV	Video Pulse Width	45 μs
Beam Current	146 Amp	Rf Pulse Width	40 μs
Beam μPerveance	2.0 μP	Rf Duty	0.0028
Beam Impedance	1200 Ohms	Rf Drive Power	4 kW

Amplitude Response Specifications and Test Results	Test Spec	Test Data
Frequency Range, 3.1 to 3.6 GHz (Min.)		3.12 - 3.61 GHz
Frequency of Max. Power Output (3.35 GHz ± 75 MHz)		3360 MHz
Maximum Peak Power Output	<10	9.5 MW
Mean Peak Power Output, 3.1 to 3.6 GHz	> 7.15	6.95 MW
Gain (Min.)	> 30	- - - dB
Bandwidth, 0 to -2 dB	> 325	360 MHz
Bandwidth, -2 to -6 dB	> 500	480 MHz
Power Variation from Smooth Curve	< 0.5	0.4 dB

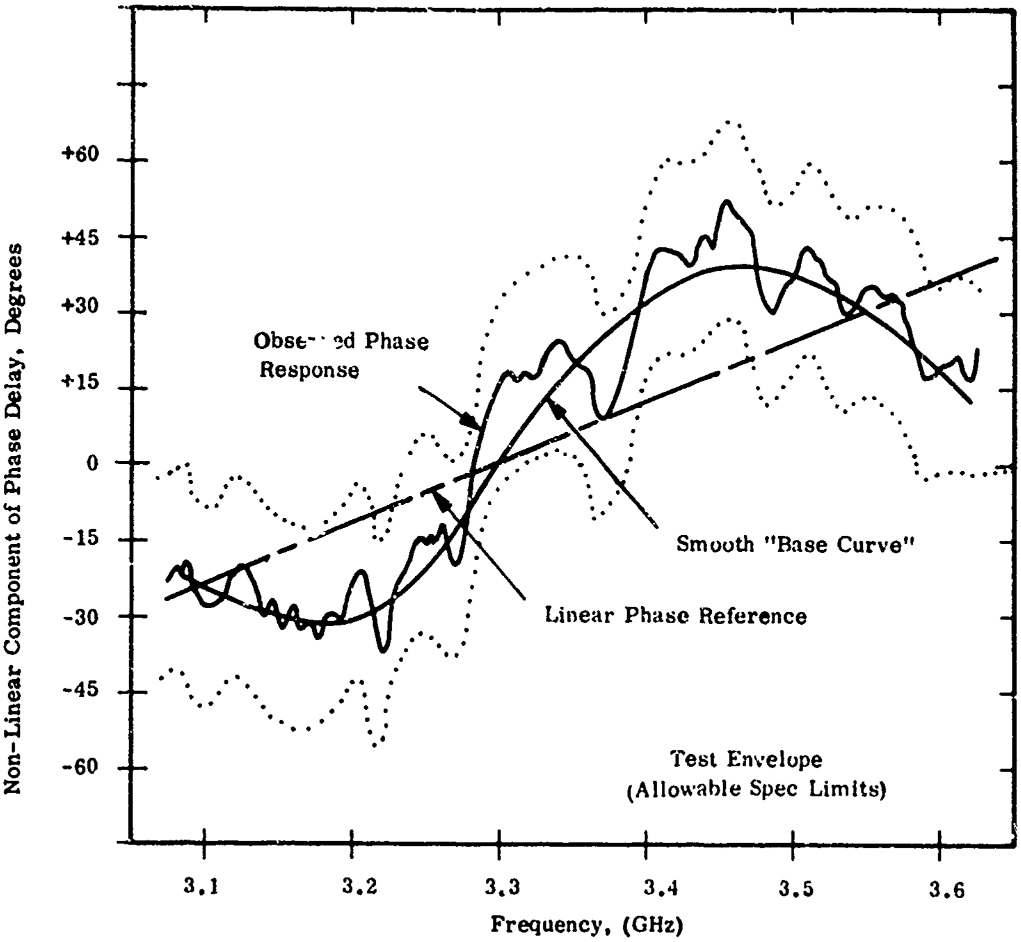
Figure 19. Amplitude Response Data for VA-915A Tube X-9, S/N 103



Beam Voltage	180 kV	Video Pulse Width	45 μs
Beam Current	150 Amp	Rf Pulse Width	40 μs
Beam μ Perveance	1.98 μ P	Rf Duty	0.0028
Beam Impedance	1200 Ohms	Rf Drive Power	4 kW

Amplitude Response Specifications and Test Results	Test Spec	Test Data
Frequency Range, 3.1 to 3.6 GHz (min)		> 3.1 - 3.6 GHz
Frequency of Max. Power Output (3.35 GHz ± 75 MHz)		3255 MHz
Maximum Peak Power Output	< 10	9.4 MW
Mean Peak Power Output, 3.1 to 3.6 GHz	> 7.15	7.8 MW
Gain (Min.)	> 30	31 dB
Bandwidth, -0 to -2 dB	> 325	425 MHz
Bandwidth, -2 to -6 dB	> 500	545 MHz
Power Variation from Smooth Curve	< 0.5	0.4 dB

Figure 20. Amplitude Response Data for VA-915A Tube X-10, S/N 104



Beam Voltage	180 kV	Video Pulse Width	45 μs
Beam Current	149 Amp	Rf Pulse Width	10 μs
Beam μ Perveance	1.94 μ P	Rf Duty	0.0006
Phase Measurement Error	± 5°	Rf Drive Power	4 kW

Smooth "Base Curve" Specifications and Test Results	Test Spec	Test Data
(a) Deviation from Observed Phase	< ± 20	~± 17*
(b) Continuous Curve	Yes	Yes
(c) Phase vs Frequency Slope Reversals (Fig.)	0	0
(d) Cyclic Deviations from Linearity (Max.)	2	1
(e) Deviation from Linearity, 3.15 to 3.55 GHz	< ± 30	< ± 25°
(f) Deviation from Lienarity, 3.10 to 3.60 GHz	< ± 50	< ± 25°
(g) Phase Voltage Sensitivity (Max.)	15	~ 13° /kV*

*Calculated

Figure 21. Phase Response Data for VA-915A Tube X-10, S/N 104

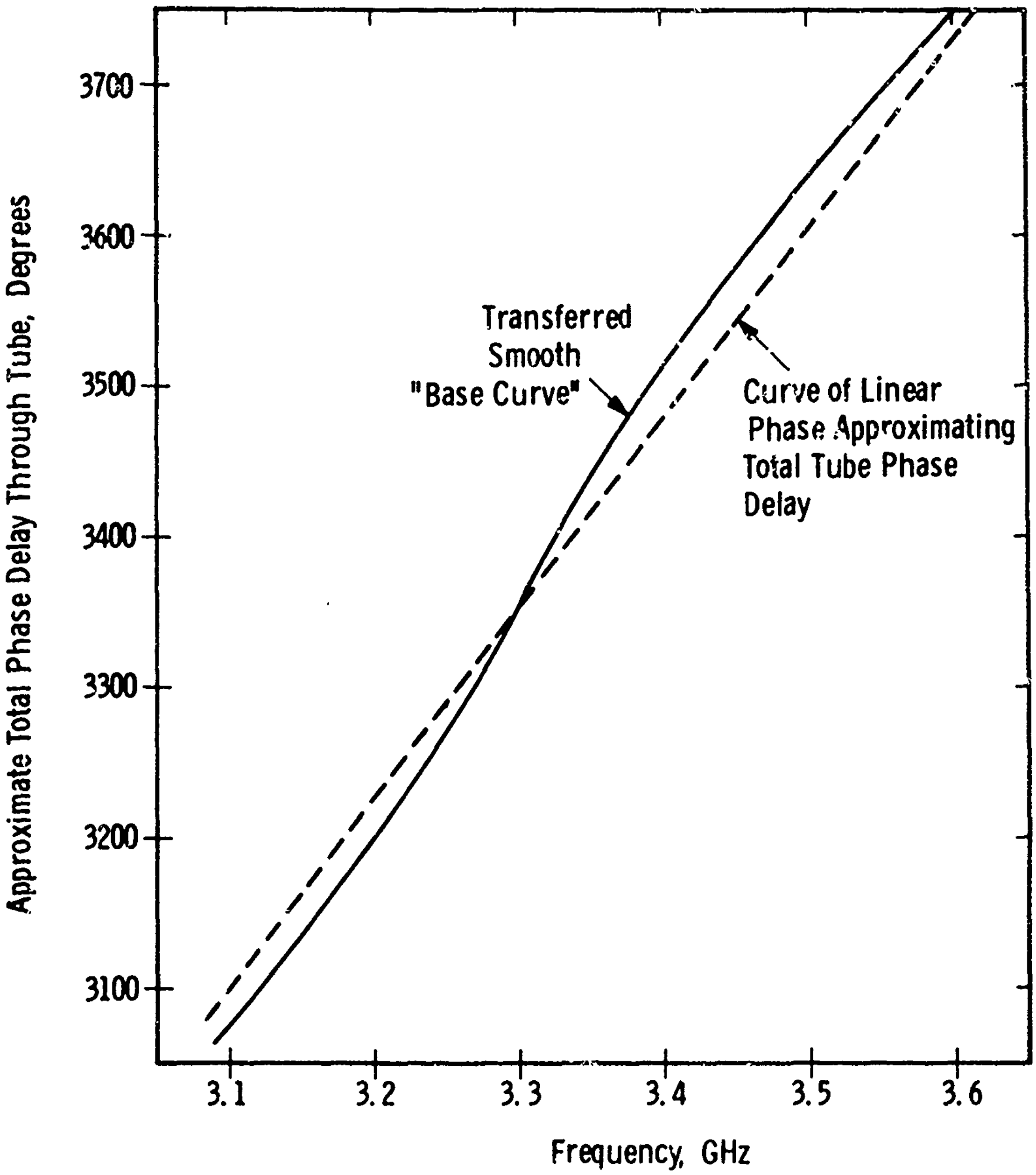


Figure 22. Comparison of Smooth "Base Curve" with Curve of Linear Phase Approximating Total Tube Phase Delay, VA-915A S/N 104

Phase response tests indicated that the tube met all specification requirements. The data observed is shown in Figure 21. The specifications compare a smooth "base curve" drawn through the minor phase deviations actually observed to a phase versus frequency envelope that includes the specification limits (±15°) plus an allowance for phase measuring equipment error (in this case ±5°). The smooth "base curve" must fall within the test envelope describing specification limits, it must be continuous, it must show no more than two cyclic variations, and it must indicate no reversal of slope in the tube phase versus frequency characteristic. The data of Figure 21 shows the nonlinear component of phase delay versus frequency, and it is plain that the smooth "base curve" constructed through the observed phase response satisfies the first three of the stated requirements. The total linear component of phase delay through the tube is approximately 3410° at 3.35 GHz, and it varies proportionately with frequency. This is shown in Figure 22. If the smoothed nonlinear component of phase delay is added to this curve, the result is a smooth "base curve" illustrating the total phase versus frequency response. It is apparent that there is no slope reversal, despite the shape of the curve in Figure 21.

Tube X-10 was shipped to the SPTF site in September 1971. Unifortunately, the tube developed a leak during shipment, although no apparent physical damage was evident on examination at the site. Attempts to make field repairs were unsuccessful, and the tube was returned to Varian in October 1971 for further examination and repair.

V. CONCLUSIONS

VA-915A Twystron hybrid TWT amplifier tubes coming very close to meeting the full specifications of "Statement of Work PR A-6-1114," Contract No. AF 30(602)4351 have been built, tested, and shipped. In several cases, however, it has been necessary to obtain contractual waivers relaxing either the mean peak power output or the bandwidth requirements. The principal cause of difficulties in these cases stemmed from a tendency toward oscillation in either the Centipede TM_{01} C-band loop passband or in the TM_{02} X-band passband. When present, these backward wave oscillations occurred along with the main signal during amplification, or independently across the pulse in the absence of rf drive. Concomitant with them were a noticeable VacIon gas level increase and usually severe arcing. When these oscillations were suppressed, as by constraint of the electron beam diameter to a smaller size, performance in the normal TM_{01} cavity (amplifying) passband was compromised.

As presently constructed, therefore, better models of the VA-915A Twystron are just capable of meeting the full specifications; whereas models having stronger oscillation tendencies cannot meet all specifications. The present overall tube design is one that, in accordance with usual industrial practice, would be more accurately described by reduction of the specification limits in the areas of mean peak power output and bandwidth. At the present time, relatively modest changes are indicated. If the mean peak power output requirement were reduced from 7.15 mw to 6.5 mw and the overall bandwidth requirement from 500 to 450 MHz, virtually all models built to the existing design should be completely acceptable. The mean peak power output would still be equivalent to 91% of the original requirement, while the bandwidth would be equivalent to 90% of the original specification.

Considerably improved tube performance would be possible with the suppression of oscillation tendencies. A substantial background for an effort in this direction has been obtained in work with the VA-915A at Varian. The device is, after all, the highest powered broadband tube of this type in the world; and oscillation problems, though not unique, are at least substantially more severe than in lower power tubes. In addition to Varian experience, there is a large body of information concerning the Centipede available as the result of efforts at Stanford and elsewhere. Much of this relates to the suppression of oscillations. This material and brief discussion of the oscillation problem are covered in the next section.

VI. RECOMMENDATIONS

1. GENERAL

The VA-915A Twystron hybrid TWT has been carried through the development period. Three experimental model tubes have been constructed, tested, and delivered for use in the SPTF system. Several recommendations emerge from the analyses of tube performance and study of the assembly histories of these tubes and of other models built and possibly tested, though not shipped. These recommendations fall into two general categories; electrical and mechanical. The following paragraphs discuss principal areas of interest, regions where it is felt that significant improvements in tube design may be possible.

2. CENTIPEDE TWT RF OUTPUT ASSEMBLY

The Centipede TWT rf output circuit is capable of providing excellent tube gain, bandwidth, and power output at good efficiency if practical means of stability control are available. The intelligent application of oscillation suppression techniques requires a thorough knowledge of the properties of the interacting modes. While it is not the aim of this report to enter into detailed discussion of the Centipede circuit, yet it is worthwhile to summarize present knowledge through brief comment and reference to material to be found in the literature.

The Centipede TWT circuit was invented by Dr. Marvin Chodorow[1] of Stanford University in 1955. It is discussed briefly in a 1957 IRE article by Chodorow and Craig[2], where it is referred to as "The Interlaced Structure." The passband characteristics are equated with those of the Cloverleaf circuit, the principal subject of the article. A high power S-band Centipede TWT amplifier is described by Chodorow, Pearce, and Windlow[3] in a 1960 Stanford University Microwave Laboratory report. An X-band Centipede TWT was reported by Roumbanis, Needle, and Winslow[4] at the 1962 US Signal Corps High Power Tube Conference. Further information on the Centipede TWT is included in a 1962 Stanford University Microwave Laboratory report on the "Development of High Power Tubes and Related Studies."[5] Significant results in the study of oscillation suppression in high power TWT amplifiers are reported by Ivanek[6] in a 1963 Stanford University Microwave Laboratory report.

The work of Ivanek is particularly interesting and appropriate at this time, since the Centipede circuit was the principal vehicle through which means of oscillation suppression were sought. Cold test techniques were employed in the evaluation of circuit arrangements aiming at external selective loading. That is, coupling slots were introduced in the cylindrical outer wall of the Centipede circuit. These led either to waveguides having suitable loss or to a cylindrical external lossy region. Coupling slots connected into individual lossy waveguide loads were also considered. Early efforts dealt with special types of couplers, which gave promise of working well over relatively narrow bandwidths. The possibility of using systems of couplers with overlapping frequency coverage was considered. An alternate arrangement of leaky wall coupling was investigated extensively. An experimental structure of this type, provided with four coupling slots per section, gave an 825 MHz suppression bandwidth within which the TM_{01} C-band loop passband insertion loss was greater than the necessary minimum, about 0.7 dB/section. Double this value was obtained over a 510 MHz bandwidth, with the maximum reaching 2.5 dB/section. The effect on the dispersion characteristic and on the interaction impedance of the TM_{01} S-band cavity (amplifying) passband was negligible. The increased structure attenuation was measured as about 0.1 to 0.2 dB per section in the range $\beta L = \pi/4$ to $\beta L = 3\pi/4$, the region encompassing the normal operating frequency range of the circuit.

An arrangement of coupling slots opening into the Centipede cavities instead of the volumes enclosed by the circuit section loops required structure modifications but offered the definite advantage of simultaneous suppression of oscillations in both TM_{01} C-band loop passband and the TM_{01} S-band cavity passband π-point. With choice of proper coupling slots and external loading the interaction impedance of the

TM_{01} S-band cavity passband in the region of $\beta L = \pi$ was reduced essentially to zero. There was little effect on the impedance below $\beta L = 3\pi/4$, the structure attenuation reaching values of approximately 0.1 to 0.3 dB section in the range $\beta L = \pi/4$ to $\beta L = 3\pi/4$.

The Ivanek report outlines a procedure which, in principle, results in the suppression of oscillation tendencies in both the TM_{01} C-band loop passband and the TM_{01} S-band cavity (amplifying) passband π-point. The method could certainly be extended to cover the TM_{02} X-band passband as well. The cold test techniques employed in the mode suppression study made use of materials and structures not suited for use in conventional microwave vacuum tubes. "Eccofoam" and "Eccosorb" were the lossy materials. These had dielectric constants in the range of 1.8 to 10 and dissipation factors in the range of 0.009 to 1.2. "Eccosorb" samples had insertion losses in the range of 5 to 15 dB, depending on type.

A relatively new lossy dielectric material is now available, one suited for use in microwave vacuum devices. It is "Carberlox", a beryllia body with silicon carbide particulates. Various characteristics may be obtained. Tests at 8520 MHz have indicated controllable attenuation values in the range of 7 to 25 dB per centimeter, corresponding to loss tangents in the range of 0.2 to 0.5, and dielectric constants in the range of 20 to 44. Electrical resistivity varies from 10^{15} to 10^{2} ohm-cm. In addition, "Carberlox" has excellent thermal conductivity. And it may be metallized and brazed into suitable electronic component structures. It is, in fact, widely used as a terminating or lossy load material in the construction of low and medium power TWTs.

The recommendation with respect to the VA-915A Centipede TWT rf output assembly is that a program be set up with the aim of achieving oscillation suppression in the TM_{01} C-band loop passband, the π-point of the TM_{01} S-band cavity passband, and the TM_{02} X-band passband using materials suitable for incorporation into the vacuum structures of microwave tubes. The program envisaged would consist of two phases: first a cold test effort in the manner of Ivanek, and secondly the construction and test of at least one hot tube (possibly a demountable version). The proposed changes, in which some sort of loading system will be located external to the actual Centipede circuit elements, involve the present rf output circuit cooling jacket (now surrounding the rf output circuit) and various other parts. There is sufficient room to accomplish these modifications inside the present shroud. Figure 23 shows a tube with shroud removed. The circuit loading changes would fit inside the present diametric constraints of the tube.

3. MULTICAVITY BROADBAND KLYSTRON ASSEMBLY

The successful suppression of competing oscillatory modes in the Centipede TWT rf output circuit should make for substantially improved performance in the VA-915A. Gain, bandwidth, and efficiency should all benefit by the removal of constraints on electron beam size. The optimization of overall tube performance will still depend not only on the TWT rf output circuit, but also on the characteristics of the multicavity broadband klystron assembly. The original VA-915A circuit characteristic data was generated in 1966. The properties desired in the multicavity broadband klystron rf input assembly were established from computer calculations. Since that time, there have been advances not only in computer techniques as applied to klystron cavity design, but also in understanding of the TWT rf output circuit and the means of achieving rf input to rf output circuit compatibility in the Twystron. It would be worthwhile to re-examine the properties of the two circuits in the light of present day knowledge and to modify the klystron cavities in accordance with such a study. Present information, stemming from the 1966 computer calculations, is that the first three klystron cavities are too lightly loaded. The external Q's (Q_e) should be reduced. Should re-examination of the rf input circuit properties result in a similar finding, then it would obviously be desirable to expend further effort toward achieving the desired loading.

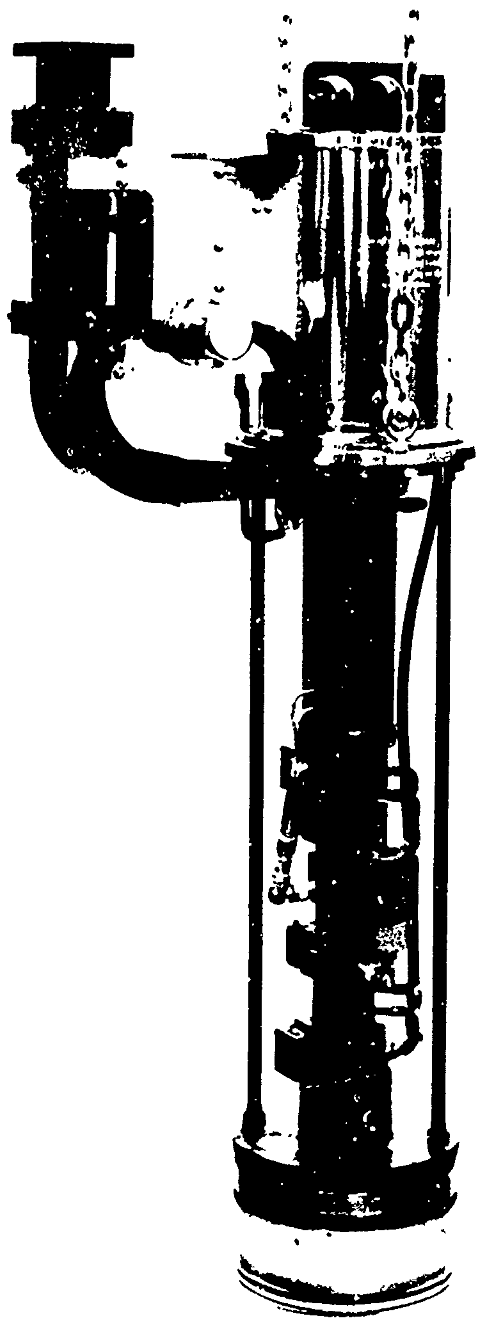


Figure 23. VA-915A Twystron Hybrid TWT (Shroud Removed)

The recommendation with respect to the multicavity broadband klystron assembly is that the indicated work be undertaken. The program would consist of three phases; 1. computer work in re-examining the rf input and output circuits, 2. cold test efforts to obtain the desired cavity properties, and 3. the construction of at least one tube to prove out the work.

4. MECHANICAL DESIGN

The main considerations in microwave tube mechanical design concern dimensional accuracy, ease of assembly, and vacuum integrity. It is frequently a long, hard row from the drawing board to the completed tube; weak points are often uncovered only through experience. The more complex the tube structures, the more difficult the problems of assembly. In the usual case, after a new tube is developed, a period of product design ensues, during which most or certainly many of the troublesome mechanical features are changed. This work is usually accomplished during the early stages of production. In the usual case there are substantial numbers of models to be constructed following acceptance of the basic electrical design. In the case of the VA-915A Twystron, the program provided only for the development of the tube. The requirement for operating models was satisfied by the delivery of a few experimental devices demonstrating electrical performance. The assembly, processing, and test histories of the various tubes built in accordance with contractual requirements indicate many areas where mechanical improvements would be beneficial. It is recommended that any further assembly activity of VA-915A tubes be preceded by a mechanical design review based on program experience and on results observed with other and more modern tubes. The design review would be followed by appropriate changes. The ultimate effect of this effort, of course, would be greater ease of tube assembly and reduced costs.

5. SUMMARY OF RECOMMENDATIONS

Cold Test Program	1.	Perform tests on modified Centipede TWT circuit elements to determine means of suppressing oscillations in TM_{01} C-band loop passband, at the π-point of the TM_{01} S-band cavity passband, and in the TM_{02} X-band passband. Use materials and structures suitable for incorporation into microwave tube vacuum.
	2.	Perform tests on the cavities of the milticavity broadband klystron assembly to ensure proper characteristics. In particular, establish suitable external loading (Q_e) in the first three cavities.
Computer Program	1.	Re-evaluate rf input and rf output relationships. Make calculations aiming at improved circuit compatibility.
Mechanical Design	1.	Conduct mechanical design review based on experience with models of the VA-915A and with comtemporary tubes. Make indicated changes.
Tube Construction	1.	Build at least one tube incorporating the changes outlined above. (Possibly a demountable tube.)

VII. REFERENCES

1. U.S. Patent No. 3233139, "Slow Wave Circuit Having Negative Mutual Inductance Between Adjacent Sections", Marvin Chodorow, Original Filing September 26, 1955, Subsequent Filing February 1, 1966.

2. Chodorow, and Craig, "Some New Circuits for High-Power Traveling Wave Tubes", Proc. I.R.E., pp. 1106-1117, August 1957.

3. Chodorow, M., Pearce, A.F., and Windlow, D.K., "The Centipede High-Power Traveling Wave Tube", Microwave Laboratory Report No. 695, Stanford University, May, 1960.

4. Roumbanis, T., Needle, J., and Windlow, D.K., "A Megawatt X-band TWT Amplifier with 18% Bandwidth", High Power Tube Symposium, U.S. Signal Corps, Fort Monmouth, N.J., September 1962.

5. Third Annual Report, Contract No. AF 30(602)-2775, "Development of High-Power Broadband Tubes and Related Studies", Microwave Laboratory Report No. 854, Stanford University, 1962.

6. Ivanek, F., "Study of Modes and Their Suppression in Broadband Periodic Structures for High-Power TWT Amplifiers", Microwave Laboratory Report No. 1115, Stanford University, 1963. Also RADC-TDR-62-532, Contract No. AF 30(602)-2575, Project No. 5573, Task 557303.

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APPENDIX A

MIL-E-1 Specification for VA-915A Twystron Hybrid TWT

These specifications concur with those listed in "Statement of Work PRA-6-1114", Contract No. AF 30(602)-4351, presented in the MIL-E1 format and 'ncluded as a part of the final report in compliance with Sub-Item 6.2, TSAF No. S-17-1/m, 2.,c.

PRELIMINARY SPECIFICATION

TYPE VA-915A PULSED TWYSTRON® AMPLIFIER

Description: Twystron Hybrid Traveling Wave Amplifier, 7.15 Mw, 3.1 to 3.6 GHz, 30 dB Gain, Cathode Pulsed Operation, Liquid Cooled, Electromagnetically Focused, Unipotential Cathode, Oil Immersed High Voltage Bushing.

ABSOLUTE RATINGS: Notes 1, 2, and 3

Parameters	Ef	If	tk	epy	epx	tp(epy)
Units	V	A	minutes	kv	kv	μ sec
Maximum	20	45	---	200	30	45
Minimum	---	---	15	---	---	---

Parameters	Du(beam) Note 4	Beam Trans	Output VSWR	pd	Output Pressurization
Units		%		kw	psia SF6
Maximum	0.003	---	1.5:1	5.0	45
Minimum	---	95	---	---	40
				Note 5	Note 6

Applicable Documents Note 7

HV Bushing Note 2

Cooling, Liquid Note 3

Electromagnet Note 8

Mounting Support Note 9

Rf Input Type "N", UG-23/U, Note 10

Rf Output VW 284 Flange, Note 11

Mounting Position Any

X-Radiation Note 20

Vibration, Shock Note 12

GENERAL

Ref	Test	Conditions	Min	Max
(3.6)	Marking	Per Outline Drawing VA-915A J027067 Rev. E, Note 13		
4.8.5	Holding Period	t = 168 hours		

QUALIFICATION

Ref	Test	Conditions	Min	Max
1006	Salt Spray Corrosion	Omit		
1042B	Shock	Note 12		
1031A	Vibration	Note 12		
---	Acceleration	Any Position, G = 5, Note 12		
4243A	Spurious Radiation	Note 14		
4278A	Phase Linearity	Note 15		
---	Individual Harmonics	Note 16		
(4.6)	Heater Life	Notes 2 and 17	t:500	---hours
(4.6)	Shelf Life	Note 17	t:12	---months

QUALITY CONFORMANCE INSPECTION, PART 1

D-30(b)	Dimensions	Per Outline Drawing VA-915A J027067 Rev. E		
4268	VacIon® Pump Indication	After holding period	P:---	10^{-7} mmHg
4003	Pressurization	Rf Output Window	P: 25	30 psig
1143A	Body Coolant Flow	P = 36 psig; Note 3	: 3	---gpm
1143A	Collector Coolant Flow	P = 36 psig; Note 3	: 20	---gpm
1301	Heater Current	Ef = 15V nom; Notes 2,3 and 4	If: 33	43 A
4266A	Anode-Cathode Capacity	Measured in air	C:	75 pF
4271	Amplifier Power Bandwidth	Notes 5 and 11		
---	Load VSWR	VSWR = 1.1:1 max		
---	Magnetic Focusing Field	Note 8		
4303	Heater-Cathode Warmup	tk = 15 min, Notes 2, 3, and 4		

4304	Pulse Characteristics			
4306A	Beam Voltage Pulse	tp = 45μ sec max, Note 18	epy: 164	180 kV
1296	Beam Current Pulse		ib: 133	151 amp
---	Peak Power Input		pi:---	27.2 Mw
---	Beam Microperveance		K: 1.8	2.0 μP
---	Band Center Frequency	Fo = 3.35 GHz		
---	Frequency of Maximum Power		F:3.275	3.425 GHz
4250A	Maximum Power Output		po:---	10 Mw
4271A	Bandwidth (1)	Po = 0 to -2 dB, Note 19	F:325	---MHz
4271A	Bandwidth (2)	Po = -2 to -6 dB, Note 19	F:500	---MHz
4262	Amplitude Response	Note 19		
4250A	Mean Peak Power	Note 19	po: 7.15	---Mw
4253	Gain	Note 5	G: 30	---dB

References not shown in parenthese refer to paragraphs in "MIL-STD-1311A, Test Methods for Electron Tubes". References shown in parentheses refer to paragraphs in "MIL-E-1G, Military Specification for Electron Tubes". Only those paragraphs of MIL-STD-1311A and MIL-E-1G referenced in this specification shall apply.

Note 1: Referring to paragraph 6.4 of MIL-E-1G, these values are based on the "absolute system" and should not be exceeded under continuous or transient conditions. A single rating may be the limitation and simultaneous operation at another rating may not be possible. Design values for systems should include a safety factor to maintain operating within ratings under voltage and environmental variations. The life warranty is predicated on operation of the tube under the specified test conditions given on the Test Performance sheet accompanying each tube.

Note 2: The HV bushing must be immersed completely in insulating oil such as Shell Diala-AX or equivalent. The insulating strength of the oil shall be determined by the methods of ASTM Standard DT-877.

Note 3: The collector and body are cooled with either water or 60-40% Glycol-water. Cooling requirements for the tube are given in the table below:

Coolant	Tube Part	Inlet Temp	Flow
Water	Collector	12 to 67°C	20 gpm
Water	Body	12 to 67°C	3 gpm
Glycol-Water	Collector	29 to 48°C	60 gpm
Glycol-Water	Body	29 to 48°C	4 gpm

In general, the overall coolant system design should follow the recommendations given in "Methods for Eliminating Scaling in Klystron Collectors", Final Technical Report, Stanford Research Institute, Menlo Park, California, November 16, 1961.

The end of the HV bushing is cooled with forced circulation of the insulating oil. The tube socket, Drawing D027068 Rev. A, is provided with means of connecting one inch diameter plastic tubing, directing the oil into the HV bushing recess. A typical cooling installation might make use of a one-quarter HP motor-pump and three feet of plastic tubing. The tubing must provide suitable insulation and withstand any effects caused by the insulating oil. This system should be interlocked so as to prevent the application of tube heater power in the absense of proper oil circulation. The tube user must ensure that no entrapped air exists in the vicinity of the high-voltage bushing.

Note 4: Heater surge current shall be limited to less than 70 amperes.

Note 5: The individual tube rf drive requirements are given on the data sheet for each tube. In general, the stated rf drive for normal tube operation should not be exceeded.

Note 6: The output waveguide must be pressurized with clean, dry SF_6 gas within the pressure range listed.

Note 7: The following drawings provide information relating to the tube and to auxilliary equipment:

Outline Drawing VA-915A	J027067 Rev. E
Outline Drawing Tube Socket VA-915A	D027068 Rev. A
Outline Drawing, Magnet	J027069 Rev. A
Tube, Focus Coil, and Socket Outline VA-915A	D018109 Rev. F
Final Waveguide Assembly	C018710
Gasket	SK41359
VacIon Pump, Heater, Solenoid Power Requirements	P-B-05088
Coolant Requirements	P-B-05090
Tube-Transmitter Interface Requirements	P-B-05089
Rf Requirements	P-B-05091

Note 8: The electromagnet is shown in Drawing J027069 Rev. A. Correct focus coil currents for each individual tube are listed in the tube data sheet and are given on the tube nameplate. The nameplate is mounted on the collector. The proper focus coil polarity is listed on the individual data sheet.

Note 9: The tube is mounted and supported by means of the magnetic polepieces, which fit closely with the corresponding parts of the electromagnet. The tube collector polepiece is bolted in place on the top polepiece of the electromagnet.

Note 10: The tube rf input VSWR varies considerably with frequency and may be as high as 15:1 at some points within the operating band. A suitable isolator or circulator should be provided between the tube rf input and the rf driving power source.

Note 11: The tube rf output flange is a special Varian flange making use of an annealed copper gasket for rf contact to the mating transmitter part. A flange adapter section is provided with each tube. The flange dimensions are shown in Drawing C018710. The copper gasket is shown in Drawing SK41359. The rf output window requires cooling by circulated SF6 gas, by means of inlet and outlet fittings and hoses provided as parts of the window assembly. The circulating pump should be capable of providing approximately 3.2 cfm free air at 10 psig back pressure. An oil-less vacuum pump such as the Gast Model 0522-V103-G18D (or equivalent) would be suitable.

Note 12: The vibration and shock requirements assure that the tube will withstand shipment by common carriers and are conducted only when required by the tube purchase order. The shock and vibration tests are in accordance with MIL-STD-810B dated 23 June 1964, the applicable portions of this specification being:

Shock	Method 516.1 Procedure I
Vibration	Method 514.1, Para 5, Fig. 514-6

The acceleration requirement assures normal tube operation when the device is mounted as a portion of an antenna. When the test is performed, no voltages will be applied. The tube must show substantially the same test performance before and after the test.

Note 13: The nameplate will be mounted on the collector. The information given will include the following:

Type of Tube
Manufacturer
Serial Number
Date of Manufacture

Filament Voltage and Current
Beam Voltage and Current
Focus Coil Currents
Made in U.S.A.

Note 14: This test will be conducted only when required by the tube purchase order. The power level of any coherent narrow band spurious oscillation within the bandwidth 3.0 to 3.7 GHz and integrated over a 3 MHz band centered on the frequency of oscillation shall be no higher than -60 dB below the mean peak power output for the 3.1 to 3.6 GHz band. The total integrated noise and spurious power output within the bandwidth 3.0 to 3.7 GHz shall be no higher than -50 dB below the mean peak power output for the 3.1 to 3.6 GHz band.

Note 15: This test will be conducted only when required by the tube purchase order. A dynamic slow frequency sweep method of measurement employing a precision pulse phase measurement system such as that provided in Rantec Model-17, similar Wiltron, or equivalent equipment shall be used to obtain a continuous phase versus frequency plot across the operating frequency bandwidth and, if feasible, including 100 MHz frequency segments on either side of the specified band. The test equipment employed shall provide a stable electrical environment of the following characteristics over at lease 0.3 μs of the applied video and rf drive pulses:

(a) Modulator Pulse-to-Pulse Stability	Within ± 0.2%
(b) Electromagnet Focus Currents	Within ± 0.1 %
(c) Rf Drive Power, Constant	Within ± 0.3 dB
(d) Pulse Sample, Approximate	0.25 μs
(e) Phase Measuring Equipment Error	Within ± 2°
(f) Auxilliary Equipment Error	Within ± 5°

Note 15: The test shall be conducted as follows:

(a) A sufficient number of frequency sweeps shall be made to obtain phase versus frequency data containing unknown errors of measurement. This data shall be averaged to obtain a curve of reference.

(b) The known errors of measurement shall be added to the reference curve to obtain a phase versus frequency envelope.

(c) The ± 15° permitted in the phase linearity specification (RADC PR A-6-1114 dated 25 May 1966) shall be added the envelope of (b) to obtain a new and larger envelope.

(d) A smooth "base curve" shall be constructed through the actual phase versus frequency curve established in step (a). This "base curve" shall be continuous across the 500 MHz operating band with no reversal in slope of the phase versus frequency characteristic describing the curve and with no more than two complete cycles of deviation from a linear curve of phase versus frequency. Further, the smooth "base curve" shall show a deviation of less than 50 degrees from a linear curve of phase versus frequency across the operating band and less than 30 degrees over the central 400 MHz of the operating band. The voltage sensitivity of phase shall be less than 15° per kV.

(e) The tube shall have passed the test if it meets the requirements of step (d) and, in addition, if the smooth "base curve" will fit within the envelope described in step (c).

Note 16: This test will be conducted only when required by the tube purchase order. When required, the test shall be conducted to seperate the harmonics in the following sequence:

(a) Second Harmonic
(b) Third Harmonic
(c) All other Harmonics

Note 17: This test will be conducted only when required by the tube purchase order. The tube shall meet all applicable production tests upon completion of the Life Tests.

Note 18: During system transmitter use, the beam voltage pulse should be constant to within ± 0.2% regulation or better for best results. During test, the beam voltage pulse shall be flat to within ± 5.0% regulation or better.

Note 19: The referenced power output level shall be the maximum value recorded. The -0 to -2 dB bandwidth of 325 MHz will include but need not be centered on the frequency of maximum power output. The -2 to -6 dB bandwidth of 500 MHz shall include the 3.1 to 3.6 GHz frequency band. When a linear frequency modulation ramp is applied the tube to cover the entire operating band of 3.1 to 3.6 GHz, either during a single pulse or at a much slower rate, the mean peak power output across the band shall be as specified. The frequency versus amplitude response shall adhere as closely as possible to a smooth curve of no more than one half cycle with the sum of fine grain cyclic and random deviations not exceeding ± 0.5 dB.

Data for this test will be obtained through use of an X-Y plotter, showing peak power output as a function of frequency. Within the frequency band 3.1 to 3.6 GHz, if the total included area below the curve but greater than 7.15 MW is at least equal to the total area included above the curve but less than 7.15 MW, the tube shall have passed the mean peak power output test. If a smooth curve may be drawn through the peak power output versus frequency curve such that the actual curve is within ± 0.5 dB of the smooth drive, the tube shall have passed the amplitude response test.

Note 20: X-radiation shielding is included in the tube assembly around the collector to reduce the radiation level. It is the responsibility of the tube user, however, to provide such additional shielding as may be necessary so that radiation levels do not exceed federal and/or military standards for personnel safety.

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APPENDIX B

Test Performance Sheet
VA-915A Twystron Amplifier

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TEST PERFORMANCE SHEET

VA-915A Twystron Amplifier
Serial Number
Contract AF 30(602)-4351
Specification PR A-6-1114

Input Data

Heater Input	$V_h < 20$ V	Vh V	Beam V	Vo 164 to 180 kV	Vo kV
	$I_h < 45$ A	Ih A	Beam I	Io 133 to 151 A	Io A
Focus Coil Inputs	$V_c < 225$ V	Vc V	Beam Input	pi $\leqq$ 27 MW	pi MW
	$I_c \leqq 20$ A	I_{12} A	Beam Perv	Ko 1.8 to 2.0 uP	Ko uP
	I_{34} A	I_{56} A	Beam Z	Zo 1190 to 1340 Ω	Zo Ω
	I_{78} A	I_{910} A	Video PW	PW > 40 μsec (top)	PW μsec
Waveguide Pressure	P 22 to 37 psig	P psig	Coolant Flow Body	ΔP	Fl gpm
	SF6 or N2	Gas	Coil	ΔP	Fl gpm
VacIon Reading	$P < 1 \times 10^{-6}$ mmHg	P mmHg	Varian QA		Date

RF Data (See Curve Attached)

Frequency Coverage	Fo 3.35 GHz ±250 MHz (min)	F – GHz	Amplitude Response	Δpo from smooth curve ± 0.5 dB (max)	Δpo dB
RF Pulse	PW $\geqq$ 40 μsec	PW μsec	Gain	pd $\leqq$ 4 kW	pd kW
RF Duty	Du $\geqq$ 0.0028	Du		G 30 dB (min)	G dB
Bandwidth	BW 0 to –2 dB 325 MHz (min)	BW MHz		F of G (min)	F MHz
Bandwidth	BW –2 to –6 dB 500 MHz (min)	BW MHz	Spurious Radiation	Frequency	F MHz
Peak Power Output	po $\leqq$ 10 MW (max)	po MW		dB below po if in 3.0 – 3.7 band at least –50 dB	– dB
	Fo 3350 ±75 MHz	F MHz			
	$\overline{po} \geqq$ 7.15 MW	$\overline{po}$ MW	Varian QA		Date

Phase Linearity (See Curve Attached)

Phase Linearity	Δϕ (max) from linearity	Δϕ °		
	Δϕ (max) from S curve ±15°	Δϕ °	Varian QA	Date

Test Data Certification

Eng.	Date	Varian QA	Date	Gov't insp	Date

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